Electro-Optical Beam Observation

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Beam measurements
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Abstract:

Classical non-destructive beam measurements are limited in their performance by the bandwidths imposed by the physical size of the conducting components, cables and waveguides, which are used. In contrast to the limitations of all electrical systems, a light beam can be modulated at very high frequencies. Some of the techniques that have recently been developed for THz spectrography could be applied to beam observation methods in particle accelerators. Different types of bunch length monitor and beam position and profile monitors are described, using aspects of this technology that could provide single-shot bunch information without affecting the beam quality.

The basic process uses the electric field generated by the particle bunch to change the properties of a thin electro-optic crystal that is placed near to, but not in, the particle beam. A laser beam probes the crystal, in a simple system this could be a polarised Helium-Neon laser or semiconductor diode. The polarisation state of the laser beam is modulated during its passage through the crystal by the electric field of the charged particles. The laser beam can then be analysed at a distance to reconstruct the temporal profile of the electric field at the crystal, and hence infer the pulse length. The bandwidth of the system extends into the THz range, giving temporal resolutions of less than a picosecond.

Future Beam Measurement Challenges

The CLIC project [1], other linear collider and x-ray free electron laser studies will create electron beams consisting of long trains of closely spaced short pulses. The beams proposed for the CLIC two-beam accelerator exceed the capabilities of current detection techniques. The CLIC drive beam will be composed of 42000 bunches of 6ps with 2cm bunch spacing; these will be compressed in two stages to 30um(σ) length. The CLIC main beam will be composed of 150 bunches of 30um(σ) length with 666ps bunch spacing.

The technique of recombination to increase the bunch frequency has the consequence that adjacent bunches are the result of different operations through a series of horizontal deflectors. In order to monitor the performance of the machine, non-destructive bunch length and bunch position measurements will be required, which are able to resolve individual bunches in the pulse train.

Destructive techniques exist which are currently used to measure beam parameters, Transition radiation and Cherenkov light can be measured by sampling head [2] techniques or streak cameras to determine beam profile and bunch length. Time resolution of 200fs is possible with modern streak cameras, but the detector screens will not be able to withstand the destructive energy of the electron beam in future high-energy colliders[3].

Several techniques have been developed to perform non-destructive beam measurements. Short pulse lasers have already been used to directly measure beam parameters with sub-picosecond resolution [4] using Compton scattering and Thompson scattering. These techniques require high-power lasers and bending magnets to separate the x-rays or scattered photos from the electron beam and will be difficult to implement in a linear collider. Beam Position Monitors (BPMs) have the potential to measure bunch positions to an accuracy of <1um [5] but closely spaced multiple bunches require time resolved measurements to be truly useful. Wall Current Monitors have been developed at CERN with 10GHz bandwidth [6] that allow beam measurement resolutions of 100ps, but the sub-picosecond beams envisaged for future machines would have to have bandwidths in excess of 1THz.

A technique has been developed to monitor the bunch length in a pulse train [7] by analysis of the r.f. fields generated in the vacuum chamber. However, interpretation of the signals is difficult as they reflect changes in amplitude, position and timing along the pulse train as well as the average bunch length. The temporal resolution is limited by the range of frequencies that can be analysed, at present two waveguide ranges are covered, in the frequency range 28-88GHz, which allows average bunch length measurements of <1ps to be realised. The system cannot measure the length of a single bunch within a train of pulses and in order to improve the resolution, access to frequencies in excess of 200GHz will be needed.

All classical beam measurement systems are limited in their performance by the bandwidths imposed due to the physical size of the conducting components, cables and waveguides, that are used, and dispersion in cables and waveguides due to the range of high frequencies that are covered.

In contrast to electrical detection limitations, a light beam can be modulated at very high frequencies. The information can then be reliably transmitted, as the dispersion of a light-beam in air is very low. Multi-layer dielectric mirrors have recently been developed [8] which can even correct for this effect. In a suitable optical system, dispersion can be controlled to facilitate the measurement.

Recently published papers [9,10] have shown that bunch lengths can be measured using Electro-Optical detection, with resolutions of several picoseconds. This paper reviews some of the recent work on THz spectroscopy and shows how the techniques employed could be applied to beam observation methods in particle accelerators. Different types of bunch length

monitor and beam position and profile monitors are described using aspects of this technology. These could provide single-shot bunch information with <1um (position) and <100um (profile) resolution from a pulse train without affecting the beam quality.

E-O materials

An electrical signal can be used to modulate the polarisation of a light beam by inducing birefringence in a medium having a suitable electro-optic coefficient; Friedrich Pockels first demonstrated this in 1893. Applications of the effect were limited until the arrival of lasers, where Pockels cells are used as loss modulators and switches. One application that is currently under development at NASA is that of a lightning detector system [11]. The electric field generated by lightning directly modulates the polarisation of a light beam as previously described.

The electro-optic effect can be longitudinal, where the light beam is aligned with the electric field, or transverse, where it is perpendicular. Transverse cells are usually longer and as the light travels through more material, these require lower applied voltages for the same polarisation change.

The induced phase change (δ) for the longitudinal Pockels effect is given by [12]:

$$\delta = 2\pi\, n_o^3\, \rho\, V/\lambda$$

Where n_o is the refractive index for the ordinary ray (these materials are all bi-refringent) at the wavelength of the incident light (λ), and ρ is the electro-optic coefficient of the material in a particular crystal axis.
A polarisation change of 90° is achieved at the `half wave voltage' $V_\pi$, which is used as a `figure of merit'

$$V_\pi = \pi c/\omega\, n_o^3\, \rho$$

A common material used in this application is Deuterated Potassium Dihydrogen Phosphate, the coefficient ρ for KD*P is 26 x 10^{-12} m/V, the resulting half-wave voltage is 3 kV for visible light. Many other materials have been evaluated for their suitability as electro-optic devices [13,14].

The usual requirement is for a large electro-optic coefficient in order to minimise the voltage that must be applied to achieve the polarisation change. In the applications that are proposed in this paper, some of the least efficient materials may be used, as they would provide a larger linear range for a given field.

	n_o	ρ, pm/V	V_π, @546nm
KD_2PO_4	1.49	10.3	7.6kV
KD*P	1.49	26	3kV
KD_2AsO_4	1.56	19	3.6kV
RbH_2PO_4	1.5	14	7.3kV
RbD_2AsO_4	1.55	22	3.3kV
ZnTe	2.8	4	2.3kV
$LiTaO_3$	2.15	30.5	2.8kV
$LiNbO_3$	2.2	30.8	2.5kV
CdTe	2.84	4.5	2kV
GaAs	3.3	1.2	4.5kV
GaP	3.35	1	13kV

It is possible to use the crystal in a double-pass configuration, where the rear face of the detector is treated to act as a high-reflectivity mirror. The probe light would then make a double pass through the crystal, which would increase its sensitivity by a factor of two, and would enable the measurement to be performed through one small access hole into the vacuum chamber.

Electric field intensity

For the CLIC machine, there are two beams to consider, the high-intensity Drive Beam and the Main or "Physics" Beam. For each section of the linacs, the Drive Beam will consist of a drive pulse train of 2144 bunches, for the 3 TeV machine, each linac consists of 20 drive sections.

	Drive	Main
Pulses in train	2144	154
Pulse length (σ)	50um	30um
Pulse separation	20mm	200mm
Pulse Charge	16nC	0.6nC
E field at 3mm		

The two CLIC linacs will each produce a Main Beam of 154 pulses of only 30um(σ) in length. These 100fs($^1/e^2$) pulses can only be fully resolved in systems of 10THz

bandwidth. One practical limitation will be the size of the focal spot on the detector, in order to resolve these bunch lengths the diameter of the laser probe will need to be smaller than the e-pulse length. Focal points of 50um are possible with a simple lens.

The electron bunches will be relativistic, which is an important feature for this application. The intensity of the radial field is enhanced by a factor γ, so the transverse field will have the same intensity profile as the bunch itself, simplifying the calibration of the detector. The radial electric field will be dictated by the charge and the energy of the e-bunch, for a single electron the radial field is:

$$E_{(r)}=\gamma q/4\pi\varepsilon_o r^2$$

A point on the detector would be influenced by the field produced by the individual electrons within the angle $1/\gamma^2$ of the electron bunch. As γ will be large and the detector in close proximity to the beam, the instantaneous field from a compressed Drive beam bunch (σ=30um) at 3mm would be 30MV/m or 3kV on across a 0.1mm thick crystal. For measurements of the electron bunches before compression, the electron density will be lower, but this can be compensated for if thicker detector crystals are employed.

The proposed detector system, Ex.1, bunch length measurement

The basic process uses the electric field generated by the particle bunch to change the properties of a thin electro-optic crystal which is placed near to, but not in, the particle beam (fig.1). In a practical design, the crystal would be shielded from radiation around the beam, the sketches used here are schematic, to illustrate the principle of operation.

A laser beam probes the crystal; this could be from a low power HeNe laser or semiconductor diode. The polarisation state of the laser beam is modulated during the passage of the charged particles. The laser beam can then be analysed at a distance to reconstruct the temporal profile of the electric field at the crystal, and hence infer the pulse length. A balanced detector can be used, as the outputs of the polarisor are complementary, this reduces transmission and laser source variations and increases the sensitivity.

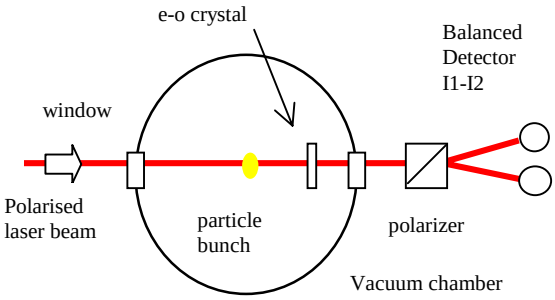


Fig.1, a simple bunch length measurement device

The bandwidth of the system extends into the THz range, giving temporal resolutions of less than a picosecond. In a practical system the diameter of the laser probe at the e-o crystal and the type of detector used would limit the resolution. The conversion to an electrical signal could be made by fast optical sensors or a sampling head, if a streak camera was used response times of <1ps would be possible. The disadvantage of such a simple system is that the detector would have to have both high sensitivity and a fast response time.

The advantages of e-o detection are in the speed of response of the electro-optic effect, and that the modulation (information) can be easily transmitted to the remote detector with virtually no bandwidth limitation. In order to achieve the high resolutions that are possible, sophisticated detection techniques must be employed.

Example 2, a high-bandwidth bunch length monitor

The system can be improved by the use of a pulsed laser synchronised to the machine frequency. The length of pulse being shorter than the particle bunch, a series of samples can be used to re-create the longitudinal bunch profile by simply changing the respective delays (fig.2). In this case, more sensitive detectors with slower response times could be used. Timing synchronisation

(jitter) between the electron bunch and the laser probe would limit the system resolution to >1ps.

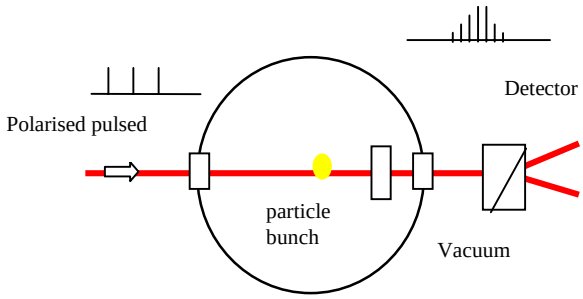


Fig.2, A high bandwidth bunch length monitor, probed with synchronised short laser pulses.

A further refinement would be to use a synchronised laser generating a short pulse that can be "stretched" using optical diffraction gratings to provide a long pulse with a linear frequency "chirp" (fig.3). If this pulse is used as the probe, it will be modulated during its length by the passage of the electron bunch. The analyser in this case would be the polarisor, a dispersing prism and a linear CCD array.

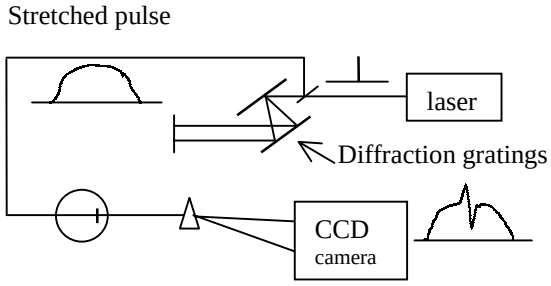
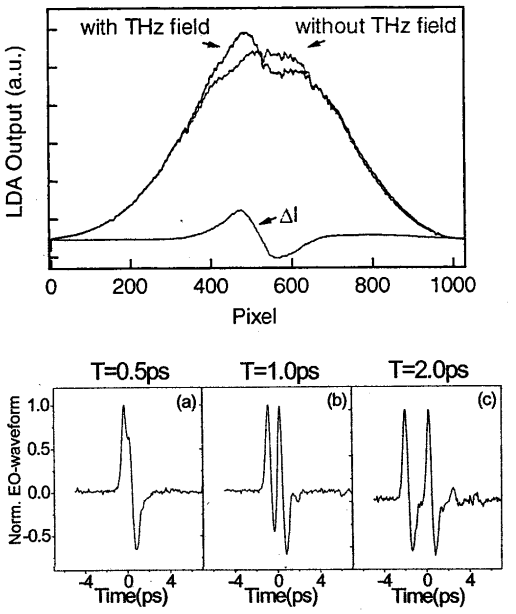


Fig.3, bunch length monitor, probed with chirped laser pulse, analysed with dispersion prism and CCD camera.

A short, bandwidth-limited pulse has a defined spectral width, angular dispersion by diffraction from the grating sets the different spectral components onto paths of different lengths. Longer wavelengths are diffracted at a larger angle than shorter ones, resulting in a longer path length. The resulting pulse will have shorter spectral components at the beginning and longer ones at the end, which is described as "down-chirped". The angular dispersion can also be achieved by refraction in prisms where shorter wavelengths are refracted more than longer ones. The pulse can also be "chirped" by passing through a dispersive medium such as glass or optical fibre, in which the refractive index is not constant over the wavelength of interest.

If a chirped, stretched, pulse is used as the probe, it will be modulated during its passage through the electro-optic (e-o) crystal by the passage of the THz pulse, which is shorter than the length of the chirped optical probe (figs.4a,4b). The analyser in this case would be the polarisor, a dispersing prism and a linear CCD array. Time resolutions of less than a picosecond have been demonstrated [15], in single-shot operation.



figs.4a,4b Temporal resolution using chirped-pulse detection

Sub-picosecond resolution would be possible if the initial laser pulses were suitably short. The measurement would also be performed on a single pulse, eliminating timing jitter problems.

Example 3, beam position monitoring

The most simple position detector has two identical crystals placed either side of the beam (fig.5). The electric field induces identical polarisation changes in the two crystals, as the field direction is opposite on the two crystals, the polarisation change

made by the first crystal will be compensated by the second. If the beam is off axis the compensation will not be equal and a signal will be detected.

In the case of short pulses, the time of flight of the particles and the laser beam must be considered. This can be overcome for equally spaced bunches in a pulse train, if the distance between the crystals is the same as the bunch spacing. Once again we have the case where the polarisation change from the first crystal is compensated by the second, although this measurement is of the mean position of the two consecutive bunches.

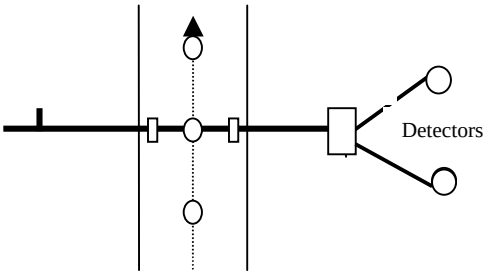
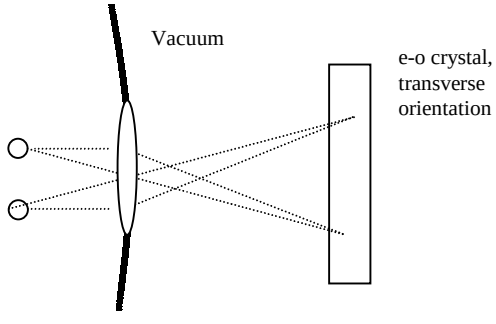


Fig.5, The separation of the crystals is equal to the distance between the e-bunches, the polarisation change is

Example 4, a beam profile monitor

Non-destructive beam profile monitors present a challenge for all types of machine. For the LHC, systems based on ionisation of the residual gas in the machine and synchrotron radiation telescopes are being developed [16].

For the present subject of e-o modulation of light, it may be possible to image the "electrical profile" of the transverse field to an e-o crystal (fig.6). This would be possible using a cylindrical lens made of high-resistivity Silicon, Magnesium Oxide or Germanium, similar to those used for CO_2 lasers and for THz-wave collimation (see annex).



The e-o crystal in this case would be orientated for the transverse Pockels effect, this also allows the laser probe to be co-axial with the beam. The usual advantage of the transverse effect is to enable longer crystals to be used, with correspondingly higher sensitivity. This is not possible in this application, as the temporal and spatial resolution will be limited by the difference in the refractive index of the material for the THz wave and the optical probe. The difference in propagation speed and the thickness of the crystal will cause a loss of resolution, for this reason the dimensions of the material will be limited in depth and width. The light beam would probe a plane through the crystal rather than a single line as in the previous examples, for good temporal resolution the beam must be focussed to a small dimension in this plane. (fig.7)

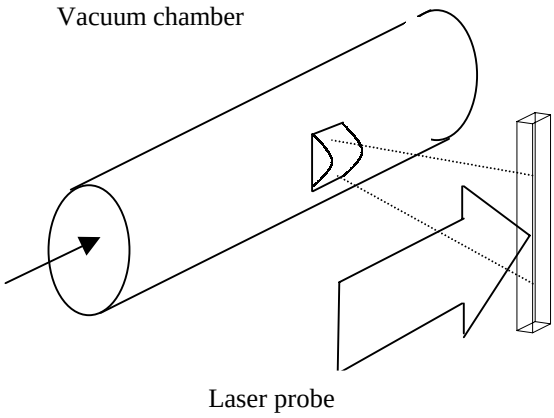


Fig.7, A beam profile monitor, isometric view.

The ability of the lens to image the electric field profile onto the e-o material would dictate the transverse resolution. The lens material will have a limited range of transparency and will have dispersion over that range. As the electric field is composed of spectral components with wavelengths over several orders of magnitude, a

compromise between bandwidth and resolution will be imposed.

The lens could be realized as a diffractive element, at the wavelengths of interest it would be possible to photo-etch a suitable phase mask onto a thin semiconductor window. Hybrid optics have also been developed, where a refractive element also has diffractive surfaces, in order to correct chromatic defects. It should be possible to create such a hybrid lens for this application, an alternative would be the use of a parabolic mirror, which has no chromatic dispersion or absorption problems.

The final analyser would need to preserve the spatial information, so a CCD camera or detector array would be suitable. The same series of developments using pulsed laser probes and chirped-pulse laser probes could also be applied for time-resolved monitoring.

Chirped-pulse manipulation and detection

Chirped optical pulses can be manipulated further in order to reduce the response time requirements of the final optical detector [17]. The process uses linear dispersion in an optical fibre and allows an optical pulse to stretch in a controlled way (fig 8). Bandwidth-limited pulse has a spectral width that is inversely proportional to its width, for a pulse of 160fs, the minimum spectral width is 60nm.

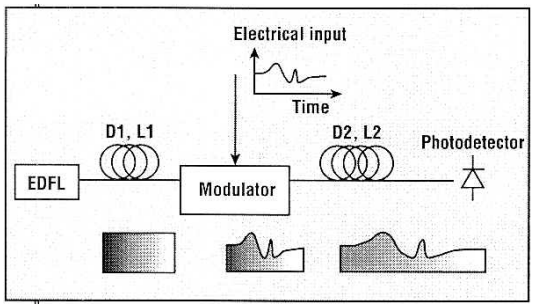


fig.8. Time-stretch technique (from ref. 15), 'EDFL' represents an Erbium Doped Fibre Laser which generates short seed pulses of 160fs.

In this example, if the original laser pulse has 160fs width, it would have a spectral bandwidth of 60nm. When stretched, by optical gratings, prisms or fibre, will retain this spectral width. The short pulse is first stretched from 160fs to 20ps, by propagation through a fibre, such as SMF-28, which has a dispersion of 17ps/km/nm. After 20m of fibre, the pulse has become chirped, the longer wavelengths now arrive before the shorter ones, the overall pulse length is 20ps, the spectral width is still 60nm, but the intensity is 1/20th of the initial pulse.

The chirped pulse is then modulated by a 5ps signal in an e-o device, and passes into another length of fibre. At the end of 2km of fibre, the 5ps electron signal has stretched to 1ns, a pulse length that is within the range of current digitisers [18]. A readily available detector and digitising oscilloscope, each having only 3GHz bandwidth, can be used to measure a 5ps pulse, in a single acquisition.

Potential difficulties and possible solutions

There are several aspects of this technique that will require study and development before practical detectors can be used in accelerators. The radiation resistance of the electro-optic materials is unknown, although a large number of potential materials exist, they will be required to operate in an environment for which there is little data. A selection of electro-optic materials (LiNbO, BBO and KD*P), have been irradiated in the CTF for a short time and show no signs of radiation damage, these trials will continue during the next run. $LiTaO_3$ and $LiNbO_3$ have now been used in accelerators [9,10], without damage.

The electric fields associated with the electron beam specified for the CLIC machine are intense, the need to keep the vacuum chamber dimensions small and maintain a low impedance line, impose further constraints for a practical system. In conjunction with the need to maintain a uniform radial field, the detector crystal must be solidly held in the vacuum chamber. The input and output windows for the laser beam must be kept small, to avoid distorting the electric field which is to be measured, the impedance of the beam line must also be considered in the design of the detector chamber.

It is clear that the detector records the electric field to which it is exposed. In the case of CTF or CLIC diagnostics, wake-fields created by the pulse train will also be present. This technique provides the possibility of measuring these perturbing fields, but for practical systems it must be shown that they are small compared to the intensity of the field of the electron bunches. The design of the detector housing will also have to address this problem, which may require absorbing materials near the detector.

It is also possible to choose different laser wavelengths, as the phase retardation is linear, a longer wavelength will have a smaller relative polarisation change, and a shorter one would be more sensitive. As potentially dangerous, higher-power, pulsed lasers may eventually be required; the use of eye-safe Erbium-based laser materials operating at 1.7um would be an advantage, as testing and alignment can be performed without risk.

Conclusion

The methods that have been developed for THz spectrography could be used in several applications of interest for accelerators, and accelerators in their turn, are a potential source of this radiation, at energy levels that are currently unattainable.

The detector methods that have been proposed are based on the electro-optic or Pockels effect. The Kerr and Faraday opto-magnetic effects could also be used, and have the potential advantage of affecting isotropic glasses which could be more suitable for UHV applications.

The Kerr effect occurs in some isotropic glasses, the electric field causes an alignment of the molecules, and creates birefringence. The optical path length change is:

$$\Delta n = K\lambda E^2$$

Where K is the Kerr constant, between 3×10^{-14} and 2×10^{-23} cm V^{-2} for different glasses. The phase change is proportional to the square of the applied field, which reduces its attractiveness for a linear detector system. The voltages required are generally higher than for the Pockels effect.

The Faraday effect is a linear magneto-optical effect. The plane of polarisation is rotated in glass subjected to an axial magnetic field:

$$\theta = VBl$$

Values for V, the Verdet constant are 0.004 for fused quartz and 0.11(Wb/m^2) for flint glass. Terbium doped glass is also commonly used. As there is also an intense magnetic field associated with the e-bunch this could be a useful effect for use as a detector.

The existence of three optical effects; Kerr, Pockels and Faraday, ensures that there is a wide range of potential materials for this type of application.

Another aspect of the Kerr effect is of changes to the reflection co-efficient of materials when exposed to magnetic fields, this effect is being studied for application in magneto-optical recording. As this is a surface, and not a bulk, effect there may be some advantage to using this process.

The CLIC beam characteristics have been used in several examples, as they present the greatest challenge for beam measurements, but the same techniques can be applied to any accelerator. Non-destructive, single shot measurements of bunch length, position and profile would enable on-line optimisation of any accelerator, enabling the machine performance to be maximised over long periods.

The development of the proposed detectors can be undertaken at little cost, simple tests can be performed on existing machines with little disturbance to their normal running. Proof-of-principle demonstrations have already been made [10]. The techniques of e-o detection offer significant benefits for existing and future accelerators. The beams currently available in CTF2 would provide a convenient source with which these techniques could be developed for use in CTF3.

I would like to thank E.Rossa (SL-BI) for several helpful discussions and for suggesting the use of the optical fibre “pulse stretch” idea.

TeraHertz Websites:

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Univ.Frieburg, Molecular and Optical Physics. http://frhewww.physik.uni-freiburg.de/~puhd/homepage/
Oaklahoma State Uni. Ultrafast group http://elec-engr.okstate.edu/utol/publicat.htm

Or use the keywords “TeraHertz” or “T-ray” in any search engine

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