

# DETECTOR RESPONSE AND BEAM LINE TRANSMISSION MEASUREMENT WITH FAR-INFRARED RADIATION

H. Delsim-Hashemi, L. Fröhlich, O. Grimm\*, DESY, Hamburg, Germany  
E. Chiadroni, University of Rome Tor Vergata, Italy

## Abstract

Good understanding of radiation generation and transport mechanisms and of detector characteristics is essential in attempting to use frequency-domain techniques for longitudinal bunch diagnostics which are of crucial importance at short-wavelength free-electron lasers. This paper summarizes the current state of experimental verification of the far-infrared performance of a synchrotron radiation beam line at the TTF2 accelerator at DESY, Hamburg. Measurement of the polarization as function of frequency has also been found a useful tool to characterize the beam line. Furthermore, several approaches for detector response measurements are reported.

## INTRODUCTION

Various activities at the TTF2 linear accelerator which drives the VUV-FEL at DESY, Hamburg, are geared towards measuring the longitudinal charge distribution of electron bunches with coherent far-infrared radiation. All such approaches require a good understanding of the radiation generation and transport mechanism and of the detector characteristics to extract useful information on the charge distribution. Simulations and measurements of the expected transverse intensity distribution and polarization of synchrotron radiation emitted at the first bunch compressor of TTF2 have been performed. The transverse intensity scanning provided for the first time at DESY a visual image of the footprint of terahertz radiation. Detector response measurements have been performed at the FELIX facility for the wavelength range (100-210)  $\mu\text{m}$ , and first considerations on using blackbody radiation together with suitable band pass filters in the terahertz regime have been made. A Golay cell detector has been characterized with this 'hot-cold' calibration method, as well as with a method based on using a mm-wave source.

## MODEL VERIFICATION OF THE CSR BEAMLINE AT TTF2

The synchrotron radiation beam line at the first bunch compressor of TTF2 [1] has been successfully used for streak camera measurements with visible and interferometric measurements with far-infrared radiation. The initial design has been based upon simple geometric optics considerations. Recent measurements and numerical calculations taking full account of diffraction effects using a

Fourier optics code suggest however a low transport efficiency in the THz regime of only a few percent. The simulations indicate that an order of magnitude better far-infrared transmission is achievable. Before installing an improved version according to such simulations, confidence in the numerical calculations needs to be gained by comparison with measurements.

As an example, the intensity distribution measured by transversely scanning with a 2 mm diameter pyroelectric detector at the end of the beam line is shown in Fig. 1, together with the result from the simulation. Similar comparisons were done in the focal point of the final paraboloid mirror and in front of the beam line, close to the vacuum view port of the bunch compressor magnet. Agreement is currently seen on a broad scale, but fine details of the measurements are not yet fully reproduced by the calculations.

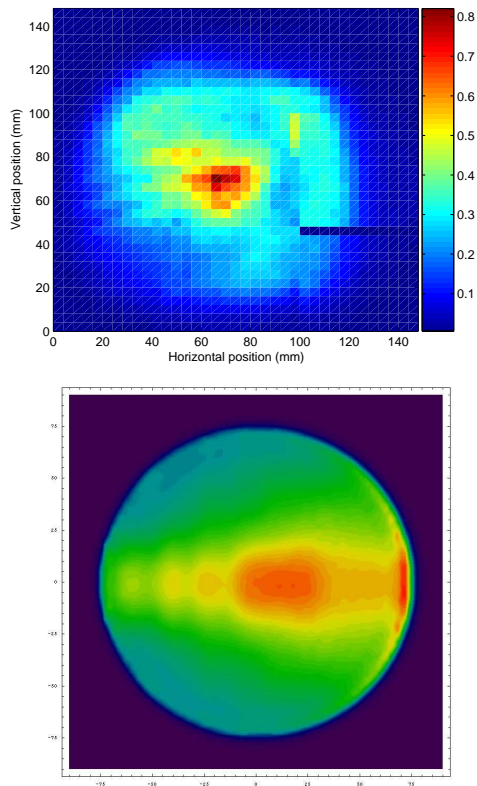


Figure 1: Measured (top) and calculated (bottom) transverse intensity distribution at the end of the beam line. A 50  $\mu\text{m}$  low-pass filter was used. The measurement is given in terms of detector voltage. The calculation covers the same area and uses at similar colour scale.

\* Corresponding author. E-Mail: oliver.grimm@desy.de

A further handle for verification purposes is the synchrotron radiation polarization as function of frequency. The source itself is expected to show a strong dependence. The measurement shown in Fig. 2 was taken after the beam line, so additional modifications to the source characteristics due to the different emission characteristics of the two orthogonal polarization components enter and are taken into account in on-going calculations.

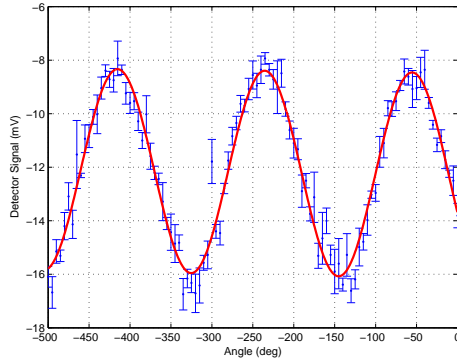


Figure 2: Detector intensity as function of the rotation angle of a polarizing wire grid. A 1.4 mm band-pass filter was used. The fit (1) yields  $p=0.52\pm 0.01$  and  $\phi_0=(-35\pm 0.6)^\circ$ .

The fit function is given by

$$I(\phi) = (I_0 + I'\phi) (\cos^2(\phi + \phi_0) + p \sin^2(\phi + \phi_0)), \quad (1)$$

where the polarization  $p = I_v/I_h$  is the ratio of two orthogonal components and  $I'$  takes into account a possible slow drift of the incoming intensity. The two components are taken with reference to a coordinate system rotate by  $\phi_0$  with respect to laboratory horizontal.

## DETECTOR RESPONSE MEASUREMENTS AT FELIX

Straightforward values for detector sensitivities are obtained by using a radiation source with narrow wavelength spectrum and known intensity. Such a source is provided by the far-infrared free-electron laser FELIX, at the FOM Rijnhuizen institute, Netherlands. The sensitivities of LiTaO<sub>3</sub> and DTGS pyroelectric detectors used for bunch length diagnostics at TTF2 were measured over the range (100-210)  $\mu\text{m}$ , an example is shown in Fig. 3.

The calculation includes the absorption in the detector crystal of thickness  $d$  and reflection at the gold back electrode, although its 15  $\mu\text{m}$  grit was not modelled [2]. This would tend to smooth the interference structure.

The FEL intensity has been monitored with a reference Joulemeter. To operate both pyroelectric and reference detector within their respective dynamic range, different attenuators had to be introduced into the FELIX beam line. Frequency-dependencies of these attenuators or of the reference detector itself cannot be separated in the results.

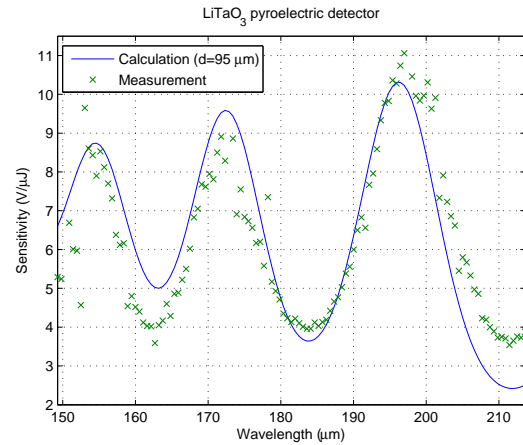


Figure 3: Sensitivity of a LiTaO<sub>3</sub> pyroelectric detector ( $\varnothing 5$  mm) measured at FELIX. The calculation takes into account absorption in the crystal, reflection at the back electrode and a Gaussian FEL linewidth (2% sigma).

A similar measurement with a 2 mm diameter DTGS detector yielded a sensitivity of about 35 V/ $\mu\text{J}$  and an interference structure compatible with 85  $\mu\text{m}$  thickness. The noise level of this slow detector, when equipped with a suitable low-pass filter, is of the order of 2 mV, thus pulse energies down to 60 pJ are measurable.

## DETECTOR CALIBRATION USING COUPLED OSCILLATORS

A local oscillator, which directly drives a mm-wave source module to 110 GHz in waveguide, has been used to produce monochromatic, linearly polarized radiation to characterise a Golay cell detector<sup>1</sup>. The waveguides are built such that only the fundamental mode TE<sub>10</sub> can propagate within the frequency band (75-110) GHz. Each waveguide is equipped with directional couplers which feed a scalar network analyzer and are used to pick up part of the signal from the source (10%) for calibration purposes and part of the reflected signal to measure the return loss. For detector calibration, a chopper to modulate the CW signal is needed and the waveguide series is interrupted, causing the emitted power to be strongly dependent on the frequency as it is shown in Fig. 4.

To reduce power losses and to ensure an almost perfect RF coupling, thus preventing back-scattered radiation and resonance effects, a conical tapered waveguide with 30° aperture has been studied (HFSS code) and built by shaping anticorodal (an Aluminium alloy) with the electroerosion technique to have at one end a standard flange with rectangular aperture ( $x=2.54$  mm,  $y=1.27$  mm) and a custom circular flange with radius of 3 mm to match the detector window at the other end.

An initial power of 1 dBm has been attenuated and modulated at 10 Hz chopper frequency, locked to a lock-in

<sup>1</sup>Collaboration with the University of Milano-Bicocca

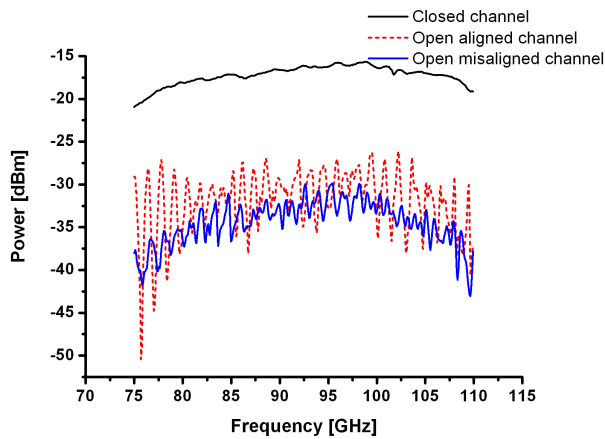


Figure 4: Source power spectrum for open (aligned and misaligned) and close channel.

amplifier to eliminate the background radiation. The frequency has been selected in the 75 GHz - 110 GHz bandwidth with a step width of 0.1 GHz. The responsivity, defined as the ratio between the measured voltage response and the incident power, is shown in Fig. 5.

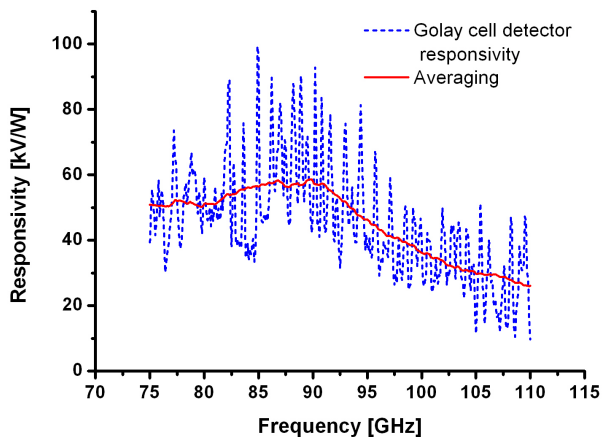


Figure 5: Golay cell detector responsivity.

On average, the responsivity follows an almost flat behaviour. The peaks are strongly dependent on the aperture between the waveguides necessary for chopping and are not a detector characteristic.

## PRINCIPLES OF DETECTOR CALIBRATION WITH BLACKBODY RADIATION

A radiation spectrum that is known from first principles is that of a blackbody, following the Planck radiation law

$$\frac{dL}{d\lambda d\Omega} = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1}, \quad (2)$$

and emitting isotropically. Isolating part of the spectrum with appropriate filters will then allow a geometry-independent relative sensitivity measurement at different wavelengths, or, with careful consideration of the geometry, even an absolute calibration. The main problem is that at temperatures for which there is sufficient intensity in the far-infrared range of interest, the spectrum rises very steeply towards short wavelengths as  $1/\lambda^4$ , requiring efficient blocking.

Specially made low-pass and band-pass filters from QMC<sup>2</sup> have been obtained to this end, but since even a small leakage at mid-infrared wavelengths would dominate any signal measured with a frequency-integrating detector, additional blocking is required. This can be achieved with fused Quartz, HDPE or Yoshinaga<sup>3</sup> filters, as can be inferred from the transmission curves in Fig. 6.

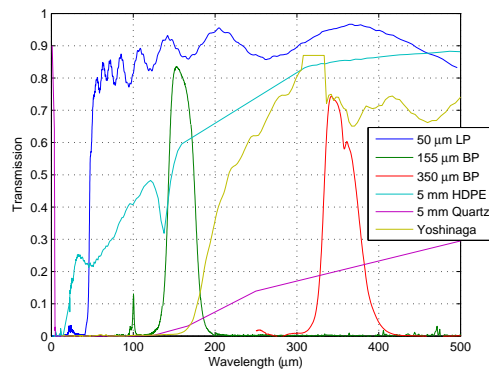


Figure 6: Filters for isolating long-wavelength contributions from a blackbody spectrum.

Infrared detectors are usually only sensitive to changing illumination, therefore a chopping setup as sketched in Fig. 7 is used. The cold blackbody is immersed in liquid Nitrogen at 77 K, the hot one at room temperature. It is essential to enclose detector and filters to avoid any chopped stray radiation to bypass the filters. The emission power in the far-infrared is proportional to temperature, so only significant rising of the hot blackbody temperature above room temperature has a useful effect, bringing a possible conflict with the operation parameters of the emitting material.

It is generally not easy to find materials that are actually black in the far-infrared, as required for the validity of (2). Reviews of suitable materials, mostly paints, can be found in [3, 4]. Studies how to construct a well-defined cavity blackbody are currently on-going at the Physikalisch-Technische-Bundesanstalt, Berlin [5], but for current experiments ECCOSORB foam, type AN-72, is used<sup>4</sup>. It is known to be a good absorber in the THz range, and thus

<sup>2</sup>QMC Instruments Ltd., <http://www.terahertz.co.uk>

<sup>3</sup>Transmission filter made from polyethylene sheets loaded with varieties of powdered crystals

<sup>4</sup>Emerson & Cuming Microwave Products, Inc., <http://www.eccosorb.com>

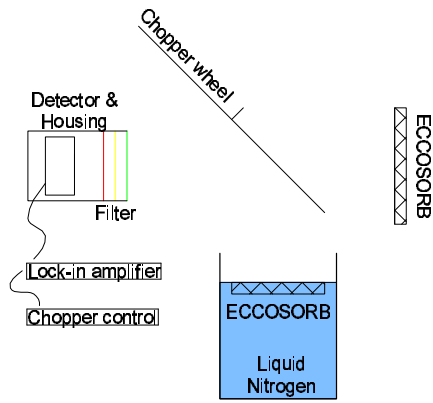


Figure 7: Setup for chopping between two blackbody sources.

expected to have a high emissivity as well.

At the University of Rome "La Sapienza" measurements with a Golay cell<sup>5</sup>, a slightly modified chopping setup (the warm emitter was directly attached to the chopper wheel) and different filters were made. By taking into account the solid angle subtended by the detector,

$$\Omega(L) = \int_0^{2\pi} \int_0^{\vartheta_0(L)} RA(\vartheta, \phi) \sin \vartheta \cos \vartheta, d\vartheta d\phi \quad (3)$$

and the emission spectrum (2), the power  $\Delta P$  on the detector can be calculated.  $L$  is the distance between the detector and the source and  $RA(\vartheta, \phi)$  the detector angular response (Fig. 8) which, assuming cylindrical symmetry, depends only on  $\vartheta$ .

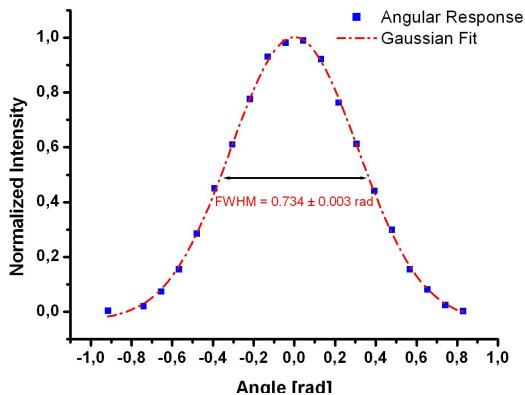


Figure 8: Golay cell detector measured angular acceptance.

Band-pass filters<sup>6</sup> with centre wavelengths of 850  $\mu\text{m}$ , 1.1 mm, 1.4 mm and 2.1 mm and 15% bandwidth have been used. To reduce the power reaching the detector and to cut visible and NIR contributions, additional Yoshinaga ( $\hat{\nu}_{cutoff} = 55 \text{ cm}^{-1}$ ) and Fluorogold ( $\hat{\nu}_{cutoff} = 30 \text{ cm}^{-1}$ ) blockers have been used.

<sup>5</sup>Property of ELETTRA - Synchrotron Light Laboratory - and provided in the framework of the SPARC collaboration, see <http://www.lnf.infn.it/acceleratori/sparc>

<sup>6</sup>Free-standing mesh filters manufactured by IKI in Moscow, cf. [6]

With the detector positioned at 3 cm from the source, the output voltage  $\Delta S$  has been recorded (Fig. 9) for the four band-pass filters. An absolute value of the detector responsivity as function of frequency can then be calculated as  $R(\nu) = \frac{\Delta S(\nu)}{\Delta P(\nu)}$ .

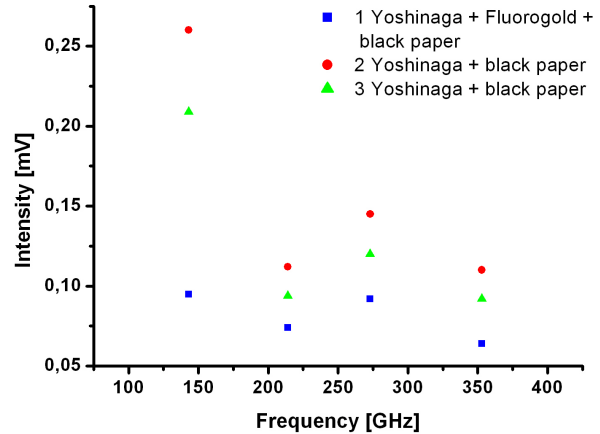


Figure 9: Detector output voltage with different blockers.

The large signal at 143 GHz (red dot and green triangle), corresponding to the 2.1 mm mesh filter, is due to the wide mesh of the filter for long wavelengths, and thus greater contribution of leaking short wavelengths. With more blockers the leakage is reduced, and complete attenuation of the visible light contribution (blue squares) is achieved if a fluorogold filter is also added.

#### Acknowledgment

We are much obliged to Dr. B. Redlich at FELIX and Dr. J. Hollandt at PTB for their assistance in preparing and carrying out the respective measurements and tests. Dr. B. Schmidt kindly supplied the Mathematica code THz-Transport. We wish to thank also Dr. M. De Petris (Phys. Dept. of the University of Rome "La Sapienza") and Dr. M. Gervasi (Phys. Dept. of the University of Milano-Bicocca) and their groups for sharing knowledge, instrumentations and time with us.

## REFERENCES

- [1] S. Casalbuoni et al., *The Synchrotron Radiation Beamline at TTF2*, Proceedings EPAC'04, Lucerne, Switzerland, 5-9 July 2004
- [2] H. Schlarb, DESY, private communication
- [3] S.M. Smith, Proc. SPIE **0967**, 248 (1998)
- [4] M.J. Persky, Rev.Sci.Instr. **70**, 2193 (1999)
- [5] J. Hollandt, PTB Berlin, private communication
- [6] R. Ulrich, *FIR Properties of Metallic Mesh and its Complementary Structure*, Infrared Physics, **7**, n.1 (1967)