TERAHERTZ DIAGNOSTICS FOR THE FEMTOSECOND X-RAY SOURCE AT BESSY

K. Holldack, S. Khan, R. Mitzner, T. Quast, G. Wüstefeld , BESSY, Albert-Einstein-Str.15, 12489 Berlin, Germany

Abstract

A longitudinal density modulation in an electron bunch caused by "femtosecond slicing" [1] in a storage ring is accompanied by a strong broad band coherent THz-light emission between 0.3 and ~10 THz at bending magnets downstream the interaction region. A technique to use the THz signal for the control of the overlap of laser and electron bunch is described. A new dedicated THz beamline at a bending magnet as well as a spectroscopic setup were commissioned in April 2004 together with the new femtosecond X-ray source at BESSY [2]. First experimental results on the emission of short THz pulses which are naturally synchronized to laser- and circular undulator light will be presented.

INTRODUCTION

The method of "femtosecond slicing" as demonstrated by the ALS in Berkeley [1] is currently under commission at the BESSY U139/UE56/1 undulators for the generation of circularly polarized femtosecond X-ray pulses [2]. One of the effects of the laser-electron beam interaction is a built-up of a longitudinal density modulation in the electron bunch which, in turn, produces pulses of coherent synchrotron radiation at following bending magnets in the far infrared (THz) spectral range after the bunch has passed a dispersive section (as predicted in ref.[3]).

For a given radiation frequency ν=1/λ (wavenumber), the totally emitted spectral power by one bunch, P(ν)=P, can

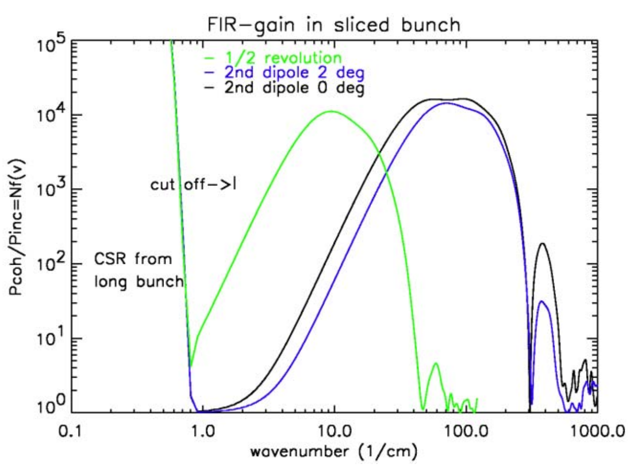

Fig.1: Coherent to incoherent power gain in the THz spectral range expected at the 2nd dipole after the interaction region and half the ring circumference.

be derived from the 'incoherent', single particle power, p(ν)=p:

$$P = Np(1 + Nf_\nu)$$

$$P = P_{incoh} + P_{coh}$$

$$\frac{P_{coh}}{P_{incoh}} = Nf_\nu$$

where f_ν is a form factor, which is the square of the Fourier transform of the longitudinal electron density dN/dz and N>>1 is the total number of electrons in the bunch. The quantity is plotted in figure 1 for three different locations in the ring: At the second dipole downstream the slicing section ~12 m behind the interaction point, in the same dipole but at a source point 20 cm behind and after 120m at half the ring circumference. Further tracking studies showed that the longitudinal density modulation and hence, the shape of the spectrum oscillate around the ring but show reduced power and a less extended high frequency tail already after 1/4 of the ring circumference. Short THz pulses carrying the time structure of the slice can be extracted therefore only at certain source points close to the interaction region. The total coherent to incoherent intensity ratio above the cut-off directly indicates the number of electrons involved in the slice.

One of the main features of the spectra in figure 1 is that the coherent radiation from the regular bunch (44 ps FWHM at 2mA) is hidden behind the cut-off frequency of ~2 cm^{-1} as mainly given by the microwave cut-off of the vacuum chamber. Therefore, a geometric separation of the THz signal emitted by the slice and the underlying bunch, as crucial for the generation of femtosecond X-rays [2], is not necessary. Also other bunches in a multibunch train will not contribute if the detection is locked to the laser frequency of currently 998.750 Hz.

A NEW DEDICATED THZ BEAMLINE

According to the simulation results above, a dedicated new infrared beamline covering the spectral range needed in figure 1 was planned together with all other components for the BESSY "femtosecond slicing" [2]. Moreover, the beamline design was made for the following other projects being prepared:

- characterization of sub-ps bunches in "low alpha optics" [4]
- electro-optical sampling using THz pulses and slicing laser
- THz pump and probe experiments using the slicing laser and/or circular undulator radiation

The beamline design was simplified compared to regular infrared beamlines [5], because they are usually optimized for providing high brilliance in the midinfrared. The new beamline as depicted in figure 2, uses edge radiation from a dipole at an acceptance of 15x60 $mrad^2$ as extracted by a plane mirror at ~0.9 m from the dipole source (modified absorber). The radiation fan is then collimated by a combination of a cylinder mirror and a toroidal mirror after passing a crystalline quartz viewport. Further plane mirrors extract the collimated beam of 50mm x 50mm size to detectors and spectrometers on the tunnel roof ~6m behind the source point. The full beam path is in vacuum to avoid strong absorption of gaseous water within the spectral range of interest. Almost the entire beam pipe is wrapped inside by a special metal foam absorber in order to avoid multiple reflections. The hardware installation showing the two mirror chambers in the tunnel is depicted in figure 3.

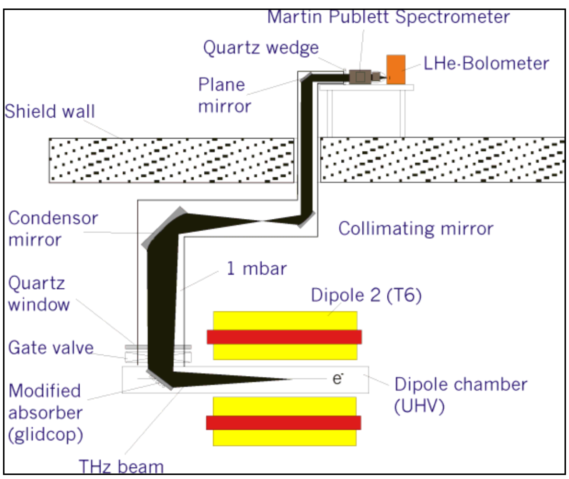

Fig.2: Sketch of the new THz beamline and the detection setup on the roof of the storage ring tunnel.

As expected the beamline shows enhanced transmission in the sub-THz range down to 1.5cm^{-1} (~50GHz) and similar transmission above 1THz like the regular infrared beamline.

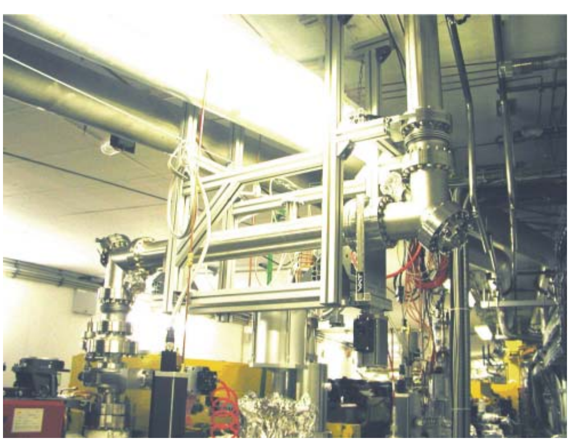

Fig. 3 Photograph of the new dedicated THz-beamline as installed at the 2nd dipole downstream the radiator UE56/1 (compare also ref.[2]).

RESULTS

After installation of the beamline in the shutdown in February/March 2004 first light was immediately observed. By the end of April 2004 a first attempt of laser electron beam overlap was performed using a laser power of 1 W at 1kHz and a single bunch beam of ~9 mA. The longitudinal timing was roughly done observing multiphoton pulses on a Si-avalanche photodiode at the diagnostic port using off axis light on the second harmonics of the modulator and attenuated laser light. The transverse overlap in the middle of the modulator is controlled by a telescope and a near infrared CCD such that the two spots show an overlap better than the rms width of the diffraction limited source image at the U139.

Even at those rough overlap conditions a first THz signal exactly at the laser repetition rate of 998.750 Hz was observed using a low frequency spectrum analyzer directly plugged to the preamplifier output of a LHe-InSb-bolometer (50GHz-2THz). Surprisingly, the signal was even visible despite of a high background signal by spontaneous bursting due to microbunching which is well investigated at BESSY above the bursting threshold of 3.5 mA [4]. In addition, the bursting pattern itself is significantly influenced and even bursting is partly triggered by the slicing. When bursting stops below 3.5mA, the pattern in figure 4 is observed on a spectrum analyzer showing all harmonics, just limited by the 1MHz bandwidth of the detector. The side bands at 300 Hz arise from phase noise of the rf-frequency indicating a longitudinal motion of the bunch with respect to the laser. A maximum signal to background of ~60 dB was found for a collinear overlap of both beams at 1.6nC bunch charge and 1 mW laser power.

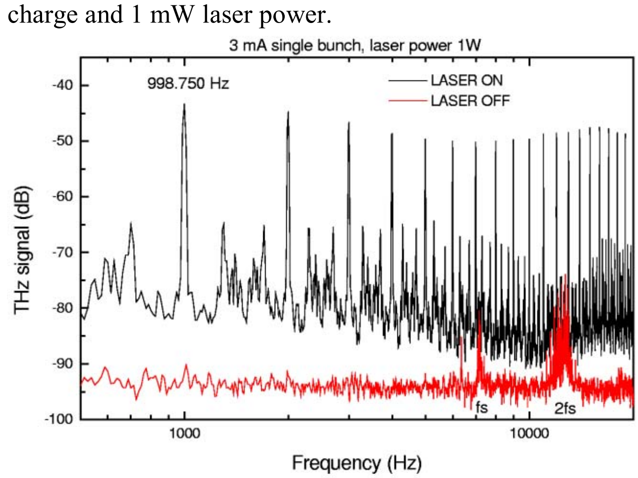

Fig. 4 Total THz signal observed on a spectrum analyzer with laser "ON" and "OFF", respectively. Parallel, sharp kHz pulses of ~10mV are observed on a scope.

The sensitivity of the THz signal to the longitudinal overlap is shown in figure 5. By plotting the square root of the signal versus the delay a bunch length of 46ps FWHM was determined in good agreement to streak camera measurements [5]. This new method of bunch shape detection is limited by the width of the slice and by rf-phase noise. However, the first measurements promise a sub-ps resolution with respect to timing and bunch length.

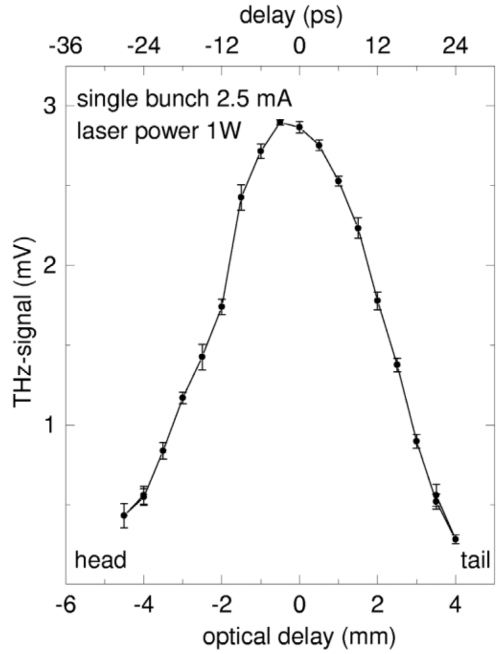

Fig.5 Total THz signal plotted linearly versus optical delay as varied in steps of 500 µm.

The energy transfer between laser and electron beam needs a resonance condition [3] between the laser wavelength and the first harmonics of the modulator U139. This condition was probed by moving the gap of the modulator insertion device while the THz signal was monitored using a lock-in amplifier locked on the laser trigger. The signal normalized to the square of the bunch current is depicted in figure 6 showing several sweeps at different ring currents. The plot reproduces a convolution of laser- and undulator spectrum. The high dynamics enables one to have even signal if the laser is resonant to sidebands of the undulator spectrum. The THz signal strictly scales with the square of the bunch current as expected for coherent synchrotron radiation. The smallest bunch current was 0.05 mA (40 pC bunch charge), where the signal was still observed at collinear overlap.

The overlap using the THz signal in other operation modes has been successfully tested within the last few weeks:

- hybrid (camshaft mode) 351 bunches, 100 ns gap
- low alpha optics in single bunch
- regular single bunch in bursting mode >10 mA
- regular user mode + hybrid bunch and 1 mrad bump in radiator (now routinely in operation)

First attempts using Si-bolometers and GeGa detectors, which are better matched to the broad spectrum, have been made to make a spectral characterization of the radiation and to obtain information on the width of the slice.

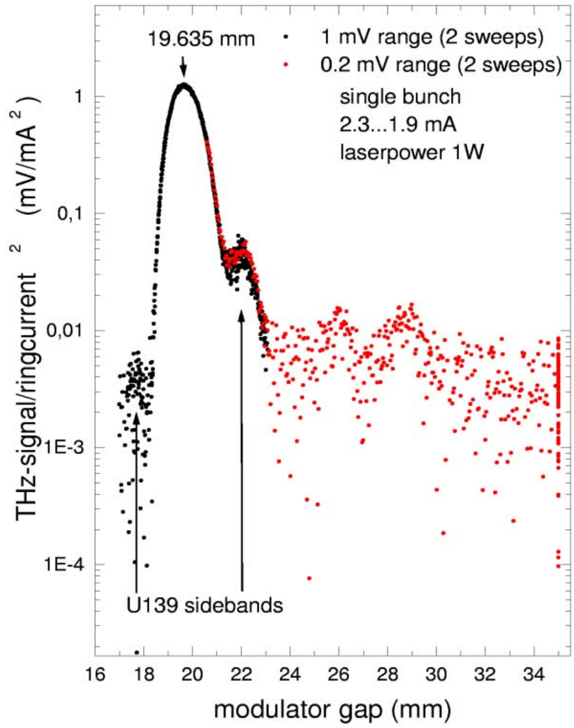

Fig.6: Normalized THz signal as detected during different sweeps of the gap of the modulator U139.

CONCLUSIONS

The THz signal emitted by a dipole downstream the slicing section is the "ultimate" tool to find and optimize the laser-electron interaction for "femtosecond slicing". A dynamics of up to 60 dB allows to obtain information on the overlap even if the timing is detuned by >100 ps and even if the beams only intersect within the modulator. A laser electron interaction on undulator sidebands can be detected even if the gap is detuned.

The THz pulses emitted at the new infrared beamline are naturally synchronized to the femtosecond X-rays, the laser as well as to the light of the U139. This promises a new class of THz-experiments on storage rings.

The successful THz-diagnostics on the slicing scheme is a model case for the optimisation of the first seeding stage at the BESSY HGHG-FEL:

ACKNOWLEDGEMENTS

We want to thank D. Ponwitz, V. Dürr, M. Dirsat, K. Blümer, W.B. Peatman, R. Müller, U. Schade and F. Schäfers for their technical support and advice..

REFERENCES

[1] A. Zholentz, M. Zoloterev, PRL 76/1996, 912
[2] H.-J. Baecker et al., EPAC 2004
[3] R. W. Schoenlein et al. Appl. Phys. B, 71, 110,2000.
[4] J.Feikes eta al. Proc. EPAC 2004
[4] W.B.Peatman et. al.,Rev.Sci.Instr. 72,1620 (2001)
[5] M.AboBakr et. al Proc. PAC 2003, p.3020