Status of the infrared undulator beamline at FLASH

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In this report we present the status of the new infrared (IR) undulator beamline, which is still under construction at FLASH. The beamline is designed to provide coherent femtosecond (fs) – picosecond (ps) IR pulses for novel pump-and-probe experiments with the fs VUV pulses from FLASH. One diagnostics port of the beamline shall furthermore be used for studies of the longitudinal charge distribution of the electron bunches in the FEL accelerator. The first part of the beamline has recently been completed and first light has been delivered into the experimental hall in mid November 2007. In the following the principle layout, status and first results of the photon diagnostic are presented.

Layout

The beamline was designed to transport useful IR radiation over the wavelength range from 200 μm to 700 nm into the experimental hall of FLASH. The layout is as such, that IR pump – VUV probe or VUV pump – IR probe experiments can be performed at the end of VUV beamline BL3 with pulses generated from the same electron bunch [1]. Thereby it is provided that both pulses should be naturally synchronized in time to one another. The IR radiation is produced by an especially designed planar electromagnetic undulator with 9 full periods and a period length of 40 cm (for details see [2, 3]). The undulator delivers useful radiation tunable in a broad spectral range from the mid infrared (MIR) to the far infrared (FIR) spectral region.

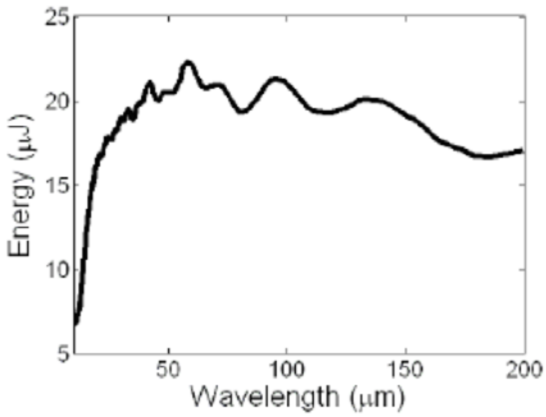

Figure 1: Pulse energies emitted into the central cone of the undulator considering the electron bunch form from reference [4] and a contributing bunch charge of 1 nC (courtesy of O. Grimm and M. Yurkov).

The wavelength of the fundamental of the device can be tuned between 700 nm to 200 μm (up to 1.5 THz). The actual emitted power depends on the electron form factor. Taking recently observed form factors into account [4] and assuming a contributing bunch charge of 1 nC, pulse energies of more than 10 μJ are expected for wavelengths longer than 20 μm (see Figure 1). The pulse duration of the emitted radiation is given by the product of the cycle time t and the number of undulator periods [5] and therefore depending on the wavelength of the undulator fundamental. Figure 2 illustrates the variation of the pulse duration emitted by the undulator from one electron bunch exemplarily for four wavelengths.

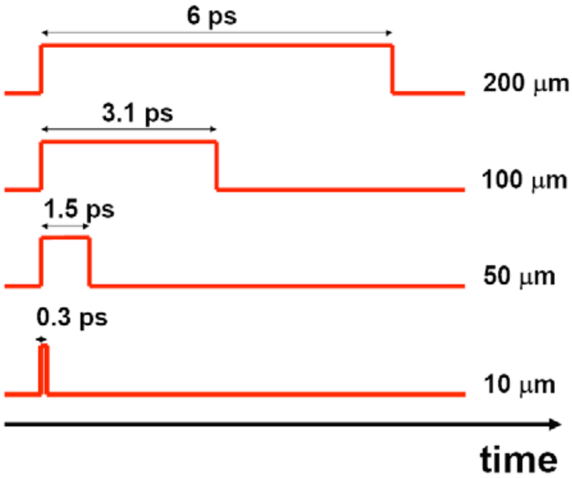

Figure 2: IR pulses emitted from the IR undulator tuned to a wavelength of 200, 100, 50 and 10 μm.

The IR pulses are naturally synchronized to the VUV pulses since both IR and VUV pulses are emitted from the same electron bunch [1, 5, 6] (see Figure 3). From the IR undulator the IR radiation diverges into the electron beam pipe with a considerably larger opening angle than the VUV radiation. After 7 m the electrons are dumped and after 7.7 m the first FIR beamline mirror M1 reflects the main part of the IR radiation into the IR beamline. A central aperture of projected 10 mm diameter allows the VUV beam to pass through (see Figure 3 and 4). Mirror M1 can be completely withdrawn from the FEL beam pipe and the aperture can be aligned to the position of the VUV beam in the pipe (for details see [7] and Figure 4). Also, M1 can be completely withdrawn when necessary (e.g. during SASE tuning of FLASH).

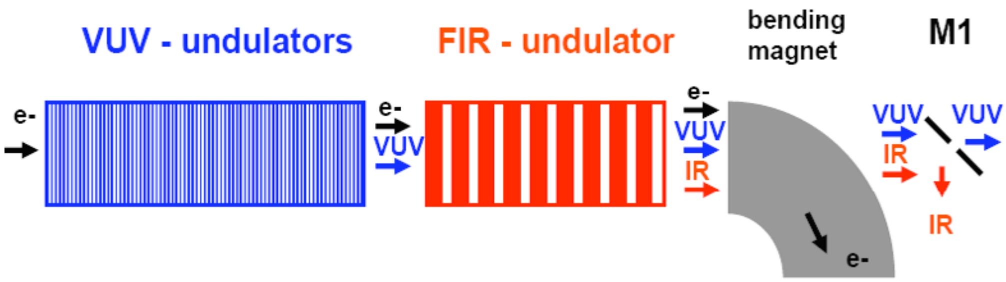

Figure 3: Arrangement of the FIR and VUV undulators in the FLASH accelerator tunnel. The FIR undulator uses the spent electron beam from the VUV undulators. The emitted IR pulse is thereby naturally synchronized to the VUV pulse. The IR beam is coupled out by the first mirror M1of the IR beamline.

The photon beamline transports the radiation over a distance of more than 60 meters into the experimental hall of the FLASH FEL. The complete beamline is operated under vacuum. After 42 m, a diamond window separates the experiment high vacuum from the accelerator ultra-high vacuum that has to fulfill specific requirements at FLASH [8].
The optical transport was optimized using codes ***ZEMAX*** [9] and ***THz transport*** [10]. By doing so, a system of 6 toroidal and 7 planar mirrors was developed (in detail described elsewhere [7]) that refocuses the beam such that, Gaussian beams considered, the apertures d in the photon beamline fulfill the d >3 w criteria [11] for wavelengths equal or shorter than 200 μm. For wavelength equal or shorter than 100 μm the optical system even fulfills the d > 4.5 w [12] criteria, consequently diffraction effects due to edges of optical elements are largely avoided.
The net transmission calculated for Gaussian beams are given in Table 1. Note that the most significant losses for the longer wavelength regime are due to the narrow electron beam pipe on the

first 7.7 m after the undulator while for the shorter wavelength the main losses are due to the central aperture in M1.

Table 1: Net transmission for Gaussian beams with different wavelength as derived from ZEMAX and not accounting for losses in the diamond window.

λ/µm	***10***	***50***	***100***	***200***
at M1	48%	85%	78%	60%
End of beamline	48%	79%	70%	42%

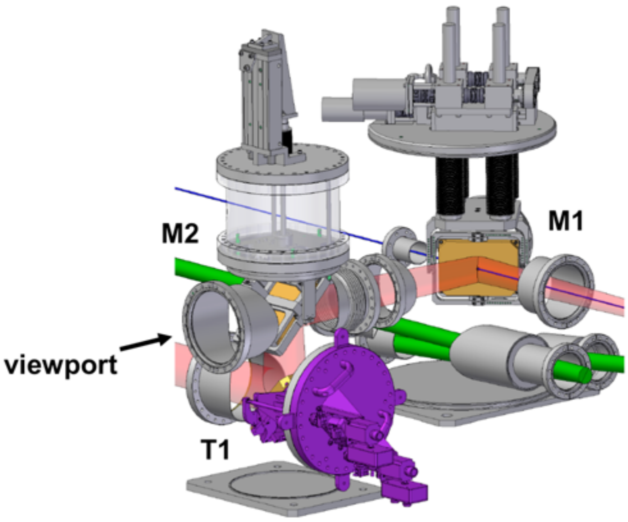

Figure 4: Layout of the out-coupling optics: A planar mirror (M1) can be aligned vertically and horizontally such that the VUV beam (blue) can pass through its central aperture of 10 mm diameter. The much wider infrared beam (red) is coupled out sideways while the synchrotron radiation fan from the dump magnet (green) can pass underneath M1. A second mirror (M2 of the IR beamline) is used to reflect the IR beam downwards onto a toroidal mirror (T1) which focuses the beam into the IR beamline. Note that mirror M2 can be withdrawn to allow out-coupling of the beam for photon beam and source diagnostics through a crystalline-quartz view port.

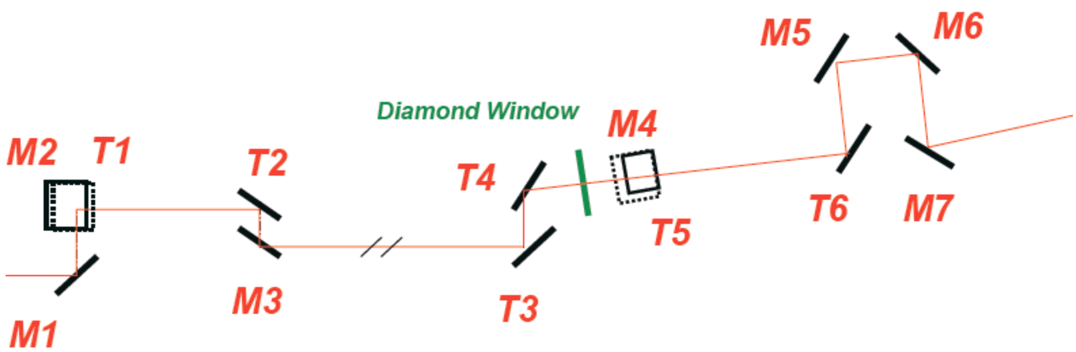

Figure 5: Optical layout of the IR undulator beamline (top view). Six toroidal mirrors and 7 planar mirrors are used to transport the IR radiation to the end of VUV beamline BL3 in the experimental hall.

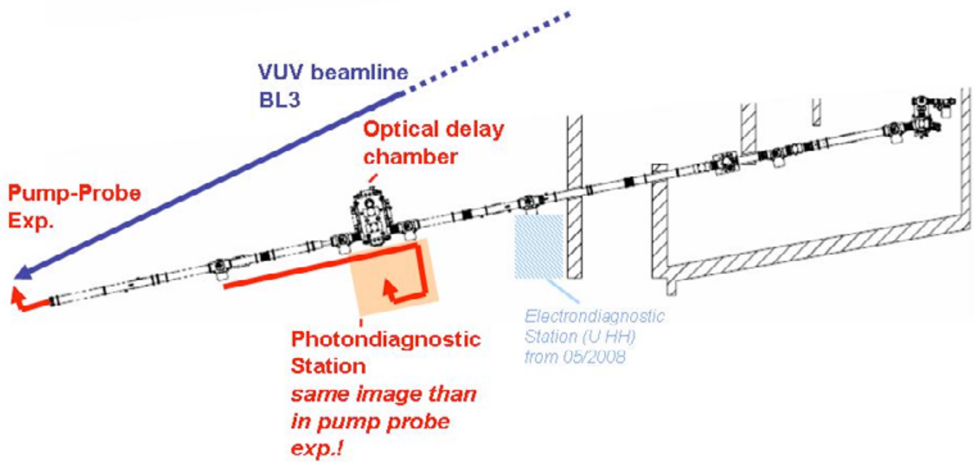

Figure 6: Principle layout of the IR undulator beamline in the experimental hall as planned to be realized in 2008. The beamline can be connected with an experimental chamber at the end of VUV beamline BL3 for pump-probe experiments. The IR beam can furthermore be coupled out and guided back to a photon diagnostic station utilizing optics equivalent to those used to transport the beam to the pump probe experiment. By doing so, the same image as that in the potential pump-probe experiment can be generated on the optical table. Spatial dependencies of the polarization, spectral content, power and pulse duration across the image in the experiment can then be investigated ex-situ.

Status

The first part of the beamline from the accelerator tunnel into the experimental hall has been completed in mid November 2007. The IR beam was then transported for the first time into the experimental hall. It was analyzed at a provisional experimental station during one single available commissioning shift.. In the following some preliminary first results are presented.

Beam profiles were measured utilizing an IR camera (see figure 7). Comparison to calculations show good agreement and indicate a reasonable first alignment of the optical elements of the beamline. The power has been measured utilizing a power meter working with the pyro-electric principle. The calibration of the detector is currently examined at the DLR by using far infared gas laser systems. Preliminary analysis indicates pulse energies close to or in the μJ regime. The dependence of the radiated power on the number of bunches was measured and showed the expected linearity (see Figure 8).

The first spectra of the FIR undulator could be taken in a spectral range from 10 to 83 μm for different tunes of the undulator fundamental. Exemplarily spectra of the undulator tuned to 60 and 70 μm are shown in Figure 9. The shown spectra are modified due to the strong absorption of humid air in this spectral range (due to lack of time the spectrometer could not be purged during the measurement). It is apparent that the spectral weight is red-shifted compared to the tuned wavelength. In a wider spectral range also strong contributions of the third harmonic of the undulator were observed (not shown). It was also observed that the undulator, even though when tuned to the far infrared, emits considerable power in the visible (VIS) and near infrared (NIR) spectral range. An upper limit for the pulse duration could be established by utilizing a Hot Electron Bolometer detector. The determined pulse width of 180 ps represents the limit of the detection electronics (a 2 GHz amplifier was used). The actual pulse duration therefore could have been much shorter.

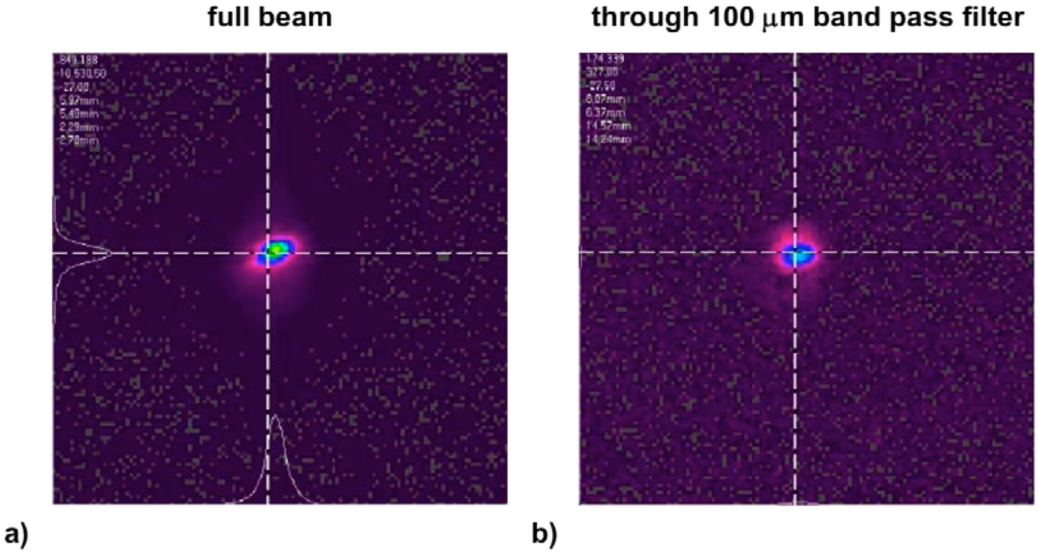

Figure 7: Beamprofile on a SPIRICON IR camera of the full beam (a) and through a band pass filter system with a center wavelength of 100 μm (b). The undulator was tuned to nominal 85 μm. The slightly elliptical shape is due to a misalignment of the outcoupling off-axis parabolic mirror infront of the provisional experimental station.

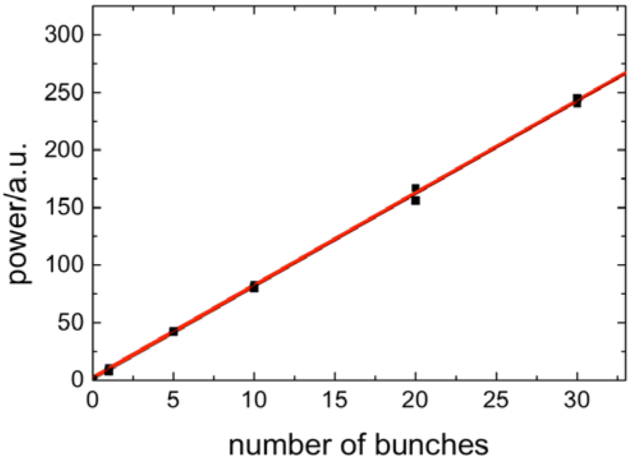

Figure 8: Dependence of the measured power on the number of bunches in one bunch-train. The bunch-trains are delivered with a repetition rate of 5 Hz. Measurements were taken through a band pass filter system with a center wavelength of 100 μm. The undulator was tuned to nominal 85 μm.

Summary and outlook

The first part of the beamline was successfully taken into operation. First beam was transported to a provisional experimental station in the experimental hall for one commissioning shift and first studies of spectral content, power, beam profile and pulse duration were carried out. The measurements of the beam profile show good agreement with calculations. Power measurements are currently evaluated but seem to indicate pulse energies in or close to the μJ regime. The determined value of 180 ps for the pulse duration is limited by the applied detection scheme so that the expected pulse length in the lower ps range may well have been achieved.

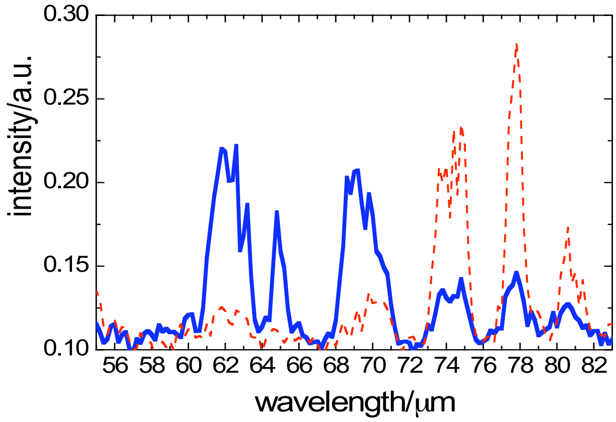

Figure 9: Spectra of the undulator radiation with the undulator tuned to nominal 60 μm (blue solid) and to 70 μm (red dashed). Clearly a red shift of the fundamental is observed in both cases. The spectra are modified by strong water absorption bands due to humidity in the laboratory air.

In 2008, the beamline will be completed, taken into operation and comissioned. First pilot IR-VUV pump-probe experiments will be carried out. Extensive commissioning is necessary to verify the potential of the beamline for regular IR pump – VUV probe or VUV probe – IR pump experiments as well as for electron beam diagnostic. Appropriate photon diagnostics needs to be developed and set up that in the optimum case will allow ONLINE diagnostic of beam profile, polarization, spectral content, pulse duration and power. Furthermore, studies of the spectral content and power of radiation emitted from the undulator in the visible (VIS) and near infrared (NIR) spectral range and their transport through the VUV beamlines need to be carried out. The aim is to verify, under which circumstances parasitic operation of the undulator is feasible.

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[12] The condition d = 4.5 w ensures that 100% of the power is transmitted and that apertures do not cause significant diffraction effects (see e.g. Optics for engineers, F. Pedrotti, Springer 1993)