LASER BEAM PROFILING AND FURTHER IMPROVEMENTS TO THE FHI FEL

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Abstract

The free-electron laser facility at the Fritz-Haber-Institut (FHI FEL) startet regular operation in November 2013. Currently, the FEL provides continuously tunable, powerful pulsed laser radiation at any wavelength between 3.6 and 50 µm covering the mid-infrared (MIR) wavelength range. The first 1½ years of operation have opened up new possibilities for research in gas phase spectroscopy of molecules and clusters, non-linear optics, and surface chemistry at the FHI. The EPICS software framework was chosen to build the control system of this facility. Actions have been taken for laser beam profiling and characterization as well as improvements to the infrastructure like the archiver system. This paper presents the next upgrade step and lessons learned during the first time of operation.

DESIGN OF THE FHI FEL

The FHI FEL includes two oscillator FELs; a MIR branch for wavelengths up to about 50 µm and a far-infrared (FIR) branch for wavelengths from, possibly, about 40 to 400 µm. The MIR FEL has been commissioned and is fully operational whereas the FIR FEL has been projected as a future upgrade. A normal-conducting linear accelerator provides electrons of up to 50 MeV energy with a beam transport system feeding either of the two FEL branches or the electron diagnostics beamline as illustrated in Fig. 1 [1].

Electron Accelerator

The accelerator system was designed and build by Advanced Energy Systems, Inc.. It combines a thermionic electron gun, a sub-harmonic buncher cavity, and two S-band (2.99 GHz) standing-wave copper linacs. The first of the two linacs accelerates the electron bunches to a constant energy of 20 MeV. The second linac accelerates or decelerates the electrons to a final energy between 15 and 50 MeV. The accelerated electron bunches from bunch trains (macro-bunches) containing thousands of micro-bunches at a repetition rate of 1 GHz. The micro-bunch length can be compressed down to a minimum of 1 ps rms by a chicane between the linacs. The macro-bunches are repeated at 5 or 10 Hz [2].

Undulator and Cavity

In the MIR FEL a planar hybrid-magnet undulator is located within the IR cavity. The undulator is 2 m long containing 50 periods of 40 mm. It employs permanent magnets made out of NdFeB. At a minimum gap of nominally 16.5 mm, a maximum root-mean-square undulator parameter K_{rms} of more than 1.6 is reached. This, in combination with the minimum electron energy of 15 MeV, corresponds to a theoretical maximum wavelength of more than 50 µm for the MIR system.

The 5.4 m long MIR FEL cavity is formed by an end mirror and an out-coupling mirror. These are gold-plated copper mirrors of concave spherical shape. The waist of the cavity mode is located at the undulator center. A motorized in-vacuum mirror changer permits to select one out of 5 out-coupling mirrors with different outcoupling-hole diameters of 0.75, 1.0, 1.5, 2.5, and 3.5 mm for optimized performance at different wavelength regions. In addition, the cavity end mirror is mounted on a precision translation stage allowing for fine adjustment of the cavity length with 1 µm repeatability [2].

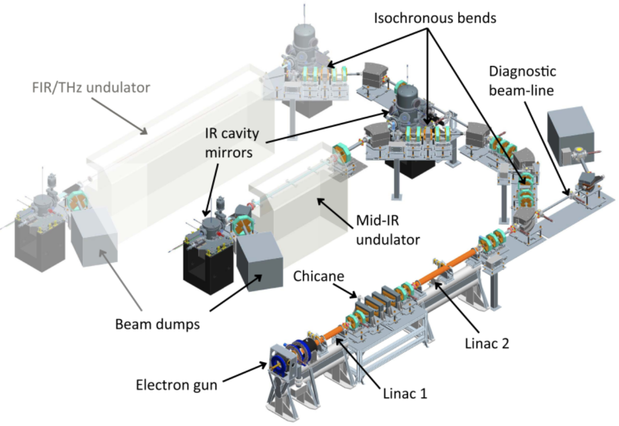

Figure 1: Overview of the FHI FEL installation.

LASER BEAM PROFILING

The IR pulses coupled-out from the FEL cavity pass through the evacuated IR beamline and propagate a distance of 18 m from the FEL vault to the diagnostic station located in the lab building. There the spectrum of the IR radiation is measured by an in vacuum Czerny-Turner grating spectrometer allowing for online monitoring of the FEL spectrum for each individual macro pulse. In addition, various commercial IR detectors are in use to determine the intensity of the FEL-pulses at different levels of sensitivity and temporal resolutions [2].

Fast IR Detector

A very fast IR detector (VIGO PEM-10.6) with sub 250 ps time resolution and an active area of 2 mm x 2 mm is used to detect individual micro-pulses. Figure 2 shows a measurement with this detector used in combination with a fast (4 GHz) oscilloscope without additional electrical amplification. At the standard micro-pulse repetition rate of 1 GHz individual micro-pulses are clearly resolved with a modulation depth of more than 50%. As can be seen in Fig. 2 this detector allows observing intensity changes on the single micro-pulse level.

Pyroelectric Linear Array

A pyroelectric linear array detector with 128 elements and a total width of 1/2" (DIAS Infrared 128LT) is

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mounted to the spectrometer and allows for monitoring the FEL spectrum in-situ for each individual macro-pulse (Fig. 3).

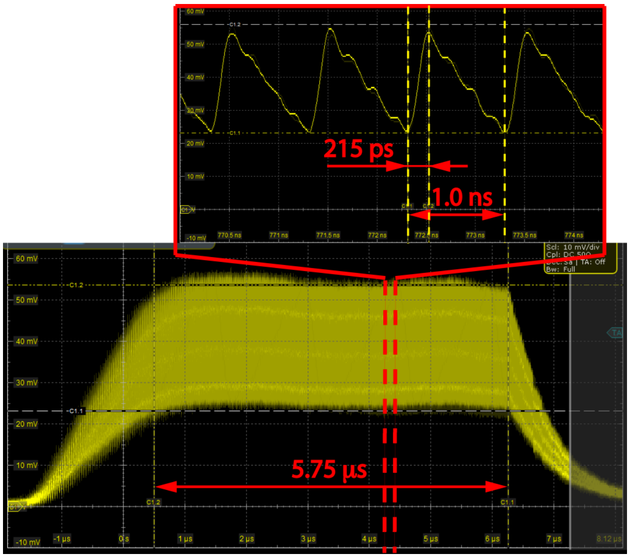


Figure 2: Detection of an FEL macro pulse at 6 µm wavelength with partial resolution of micro pulses.

The interface to the array is realized with a rtd DM6430HR 16bit, 100kHz Analog I/O PC104 module connected to a syslogic NETIPC/6. Debian Linux is used on the CPU board booting from CF card. The EPICS Input Output Controller (IOC) running on this board implements device support for 'pyroArray'. A waveform record holds the profile of the last laser shot.

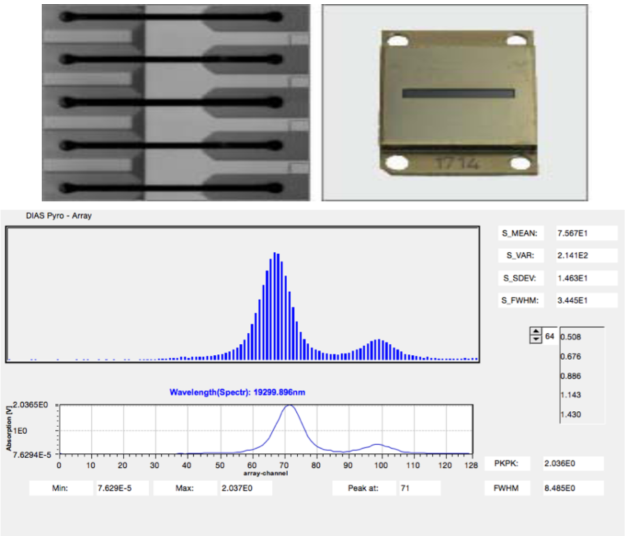


Figure 3: Pyroelectric Linear Array, OPI.

Standard Commercial Detectors

A 46 mm diameter, large area powermeter (Ophir PE50BB) is used on a daily basis to determine macro-pulse energies. Several small area (4.5 mm x 4.5 mm) pyroelectric detectors (Eltec 420M7-0) combined with in-house made amplifiers are in use to monitor the temporal shape of the FEL macro-pulses.

Pyroelectric Cameras

With pyroelectric cameras images of the laser beam profile can be obtained. Displayed in 2D or 3D views, the operator can immediately recognize beam characteristics indicating laser performance. This instantly shows detrimental laser variations. This allows for timely correction and real-time tuning of laser parameters. We use the following two camera systems :

- Spricon Pyrocam IV, 1.06 – 3000 µm, 320 x 320 elements, 80 µm x 80 µm element size, pulse rate up to 1 kHz, external trigger.
- DIAS PyroView 160L compact+, 8 – 14 µm, 160 x 120 elements, fixed measurement frequencies (70 Hz, 35 Hz, 17.5 Hz, …).

Both cameras are read out and controlled by the EPICS areadetector framework. The aravis lib is used, the camera interfaces follows the GenICam standard.

The Spiricon camera fulfils our needs but is expensive. We looked about for alternative systems. The DIAS camera works just in a limited range from 8 to 14 µm and uses fixed internal trigger frequences. Nevertheless we could integrate the DIAS PyroView by triggering the FEL with the internal clock of the camera at 4.375 Hz.

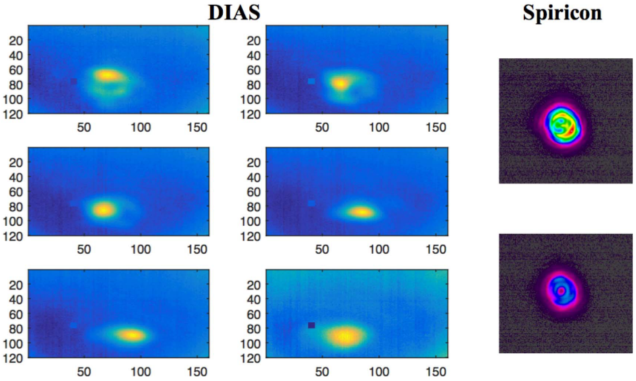


Figure 4: Images taken with areadetector.

Autocorrelation Measurement

In addition, a sensitive liquid-nitrogen cooled mercury-cadmium-telluride (MCT) detector (Judson J15D24) is used for detection of low-intensity signals such as, for instance, higher harmonic signals. Even for the fast IR detector (Fig. 2) the time resolution is by far insufficient to reveal the length and shape of the individual ps-long micro-pulses. For this reason we have installed an autocorrelation setup, shown schematically in Fig. 4, to characterize the micro-pulse shape. FEL pulses are split by a 50:50 ZnSe beam splitter (Edmund Optics). The length of one of the beam paths can be varied by a precision motorized translation stage to adjust the relative temporal delay between the two partial beams. Both beams are separately focused by 6" focal-length mirrors onto the same spot on a CdTe crystal (MaTeck GmbH) with an angle of ≈ 30º between the beams [2].

At temporal overlap of the pulses from both paths, nonlinear effects in the CdTe crystal lead to the generation of second harmonic (SH) radiation which is emitted in the direction exactly in between the reflected fundamental beams. After spatial filtering to block the fundamental beams, the SH signal is detected with the liquid-nitrogen cooled MCT detector.

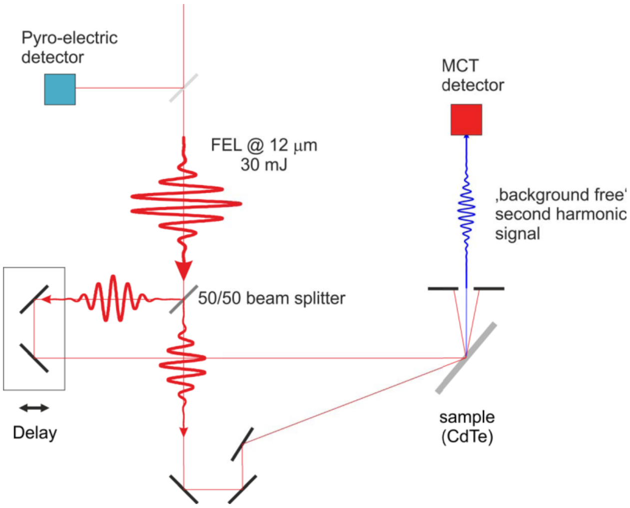


Figure 5: Autocorrelation setup, second harmonic signal.

ARCHIVER APPLIANCE

The previously used EPICS ChannelArchiver was replaced by the ArchiverAppliance developed by Murali Shankar at SLAC. We run two server systems (DELL PowerEdge R730/0599V5) in a cluster configuration. These systems are equipped with 128 GByte main memory, 4 SSDs and two 10 Gbit/s ethernet interfaces. The operating system used is Ubuntu 14.04.3 LTS. The two systems (aa0 and aa1) operate different networks. Within the FEL-LAN (10.0.0.0/23) aa1 is sampling the requested PVs, aa0 archives the data in the FHI-LAN (141.14.128.0/20). See Fig. 6. The previously used ChannelArchiver was only connected to the FEL-LAN. We could easily import the ChannelArchiver XML configuration files into aa1. The FEL-LAN is still the "PV-hotspot". We are planning further experiments at the FHI to operate with EPICS and also want to archive the data obtained there. The access to the archived data at any appliance is ensured by a proxy function implemented in the ArchiverAppliance.

The ArchiverAppliance can use multiple stages of storage. For the short term storage (STS) we use 64 GByte of the main memory (ramdisk) with the granularity of an hour. The mid term storage (MTS) with the granularity of one day is realized with SSD storage. These two storage areas are local to the server systems. For the long term storage (LTS) both systems are using one storage gateway (Crossroad StrongBox) with the granularity "forever". The connection to the StrongBox is realized with 10 Gbit/s ethernet, NFS is used to mount the LTS.

The StrongBox is a networked-attached storage (NAS) appliance. It includes a object-based Amazon S3 interface with an underlaying RESTful API. The system supports file (NFS/CIFS) and object (S3) storage. By fusing disk for nearline storage with Linear Tape File System (LTFS) tape technology for archiving, the system delivers the performance of disk with the economics of tape in one solution. One can expand the nearline capacity by adding external FC/SAS disk arrays. A tape library (IBM TS3200) with two LTO 6 tape drives (SAS) and 48 data cartridge slots was chosen and connected to the StrongBox. This gives us a capacity of more than 240 TByte. The system can be easily expanded with additional/other tape libraries.

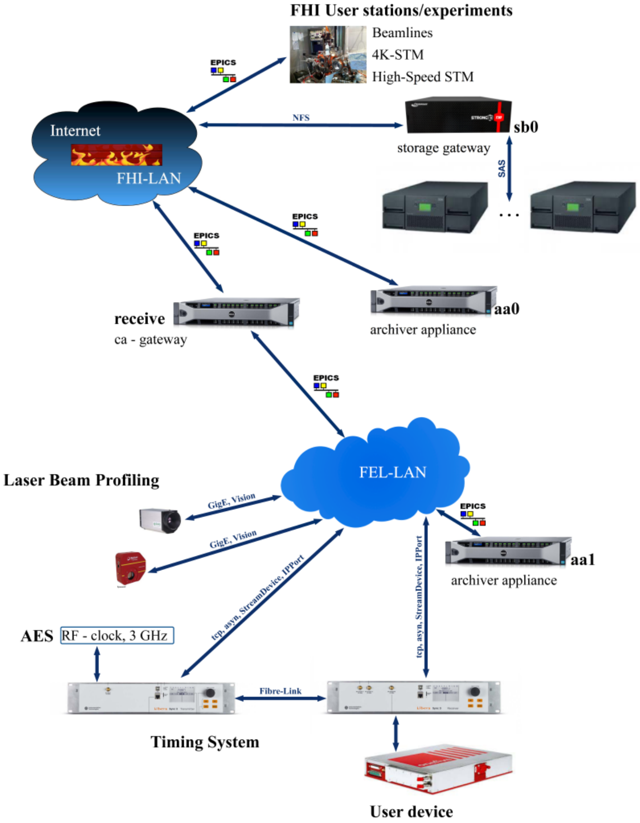
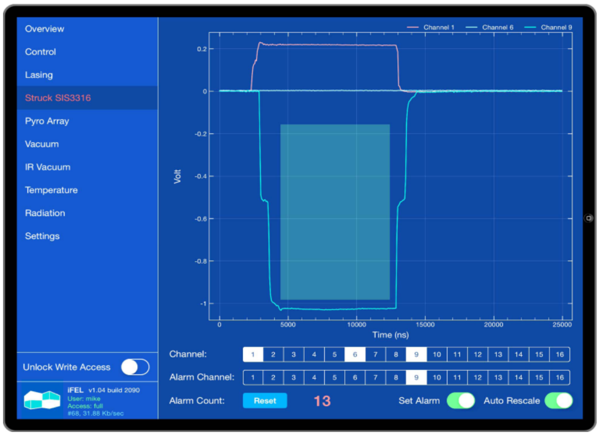


Figure 6: ArchiverAppliance setup.

MOBILE APPLICATION

To allow the operator to move freely in the institute during machine operation an iPad application was developed. The operator in charge can thus intervene at any time in the process and operate the machine (start trigger, stop trigger, adjust LLRF amplitudes and phases). A few important OPIs have been reimplemented (Fig. 7) using the Xcode development framework. These parts are now written in ObjectiveC. The communication takes places via https to a gateway running a standard Web-Server (apache, modPHP). This gateway reads the PVs out of the EPICS-IOCs using channel access (perl) and caches some of the PVs (trend data) into a SQL database on the gateway.



Alarm Count: 13

iFEL v1.04 build 2090
User: mike
Access: full
#68, 31.88 Kb/sec

Figure 7: Screenshot iPad App.

TIMING SYSTEM

To enable pump probe experiments (see following section) the clock signal of the accelerator must be delivered jitter free to the user stations. A Libera Sync 3 system was chosen for transmitting the high-performance RF-oscillator to such an beamline end-station. The system assures clock signal distribution with down to femtosecond-level added jitter. The libera system is integrated in the EPICS control system using StreamDevice with asyn over IP. See Fig. 6 [3].

FUTURE MACHINE UPGRADE

Over the last century, linear optical spectroscopy, especially when being performed in the IR, contributed substantially to our understanding of molecular structures. In addition, the usage of ultrashort laser sources has allowed to go further by studying not only structure, but also the dynamics of energy flow between different modes in molecular and condensed phase systems, providing a wealth of additional information. Traditionally, these dynamical processes are studied using pump-probe techniques where two time-delayed optical pulses are applied to the sample, and the dynamics and interactions are derived from the sample response as function of time delay between the two pulses and there frequency or fluence, respectively. Typical single-color experiments allow monitoring the population relaxation of vibrational modes; however, two-color approaches give access to mode-couplings and thus may significantly enhance the attainable microscopic understanding. In particular, both MIR-near-infrared (NIR) and MIR-MIR two-color experiments are interesting, addressing couplings between vibrations and electrons and between different vibrational modes, respectively. Ultimately, it would be intriguing to make use of the high pulse energy delivered by the FEL to also “pump” (drive) molecular processes, reactions or to create new transient states by controlling multiple vibrational motions in a concerted fashion.

Furthermore, it would also be highly interesting to extend the wavelength range accessible by the FEL to longer wavelengths to study lower-frequency vibrations at THz frequencies. The modes of interest here are vibrations involving heavier atoms, for example in clusters, collective motions in bio-molecules and correlated atomic motions in complex solid materials. As these experiments address optical thin samples or require a high field strength they can be only made possible using an FEL.

We propose an extension of the FHI FEL which would enable these new classes of experiments and make the FHI FEL a worldwide unique instrument. We hereby follow two independent directions, to allow for MIR-NIR and MIR-MIR two-color operation, respectively, with the IR pulse wavelength tunable beyond the current limit of 50 µm. MIR-NIR spectroscopy will be enabled by installation of a femtosecond tabletop laser producing pulses at 1 µm synchronized with the FEL. MIR-MIR two-color operation could be achieved by installation of a second, longer wavelength undulator. Specifically, we envision this new undulator to be operational simultaneously with the existing one. This would be possible by implementing a unique design, in which an additional RF cavity is used to feed alternating electron bunches into both undulators, respectively. This is illustrated in Fig. 8. Such an approach is novel and has not been implemented yet at any other FEL facility [4].

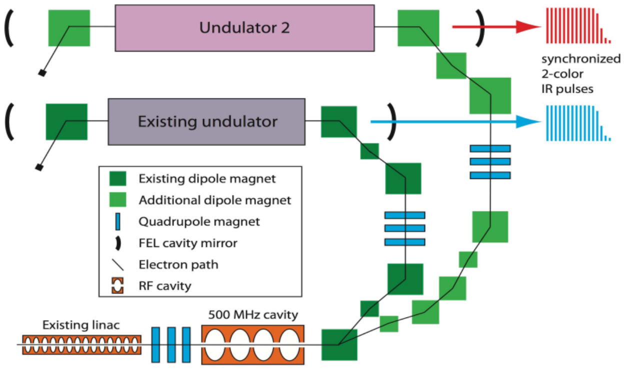


Figure 8: Future upgrade, two-color operation.

ACKNOWLEDGEMENT

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REFERENCES

[1] W. Schöllkopf *et al.*, In: Proc. Of SPIE 9512, 9512L (2015)

[2] W. Schöllkopf *et al.*, The New IR FEL Facility at the Fritz-Haber-Institute in Berlin. In: Proceedings of FEL 2014, Basel, Switzerland, 2014, 629–634, ISBN 978-3-95450-133-5

[3] A. Paarmann, private communication

[4] FHI internal, W. Schöllkopf, “Recent Developments of the FHI Free-Electron Laser Facility”, FHI Report 2015, 18th Meeting of the Fachbeirat, pp.38