INVESTIGATION AND IMPROVEMENT OF BEAM STABILITY AT THE ELBE FELs

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Abstract

At the radiation source ELBE in the Forschungszentrum Dresden-Rossendorf two free electron lasers (4-22 µm and 18-230 µm) are in routine user operation for a wide range of IR experiments for some years. The lasers are driven by a superconducting RF Linac which permits the generation of a cw beam with high average beam power. For many experiments the frequency and power stability of the laser beam is of outstanding importance. Therefore studies on fluctuations and drifts in different time scales (from µs to hours) have been accomplished and possible causes for these instabilities have been investigated. To improve the long and short term stability we developed and implemented active feed-back controls for electron energy and thus laser wavelength and out-coupled IR-beam power at ELBE.

INTRODUCTION

At the multiple beam facility Radiation Source ELBE Bremsstrahlung, X-rays, infrared radiation from FEL's and neutrons are available for routine user operation [1]. The annual beam time at the ELBE FEL's was increased from 600 hours in 2004 to more than 1000 in 2007. The FEL beam time efficiency defined as the ratio between the usable time for the user experiment and the planned time, was 90 % in 2007. The fact that 95 % of the FEL user beam time was delivered in cw mode can be considered as an impressive confirmation of the main ELBE concept which is based on a superconducting high average current accelerator as driver. The beam stability is very important for successful operation of the FEL. The stability is mainly dominated by the level of power and wavelength fluctuations mainly caused by electron beam fluctuations. In general, a continuously operating system is more stable than a pulsed one because statistical gain fluctuations during FEL oscillator up-ringing are avoided in a cw FEL. Nevertheless several sources of power fluctuations can affect the beam stability in different frequency ranges. Current fluctuations due to instable gun operation are directly connected to FEL beam power variations. Other electron beam parameters like beam position in the undulator, bunch length or energy spread influence the FEL gain and can also vary the out-coupled FEL beam power. Mechanical vibrations, in particular of the mirrors inside and outside the optical cavity, can modulate the FEL beam arriving at the users experiment. High frequency power fluctuations by resonant-like phenomena can also be observed and are described theoretically in [2].

Wavelength fluctuations are mainly associated with electron beam energy variations which can be caused by slow electron energy drift or RF phase jitter in the injector and main accelerator stages.

A first measure to improve beam stability is to avoid their sources mainly the electron beam parameter fluctuations. In many cases the sources can be localized by systematic studies of mechanical vibrations, investigations of power supply ripples and electromagnetic field measurements, in particular in the low electron energy beam line section of the injector. Beam position data logging in correlation with the out-coupled FEL beam power is also very helpful to localize sources for beam deflection like charging and discharging processes on insulators (for example beam viewer windows) or ceramic beam line elements.

In some cases sources of fluctuations are not localizable or not avoidable. In those cases feed-back systems which keep the out-coupled FEL beam power or wavelength stable are necessary. Such systems are bandwidth limited and reduce the described fluctuations in a certain frequency range. Detailed studies of the frequency spectra of the fluctuations are necessary to evaluate the potential effect of active feed-back systems.

USER REQUIREMENTS

In many ELBE FEL experiments the beam power at the user table has to be constant because fluctuations can not be monitored and taken into account at the post experiment data analysis. One-shot experiments like combined infrared pulsed high magnetic field studies which can be done in the ELBE-HLD complex [3] requires FEL beam power stability of better than 1 % during the 100 ms long magnet pulse. Other FEL experiments like investigations of two-photon quantum-well infrared-detectors (QWIP) are based on nonlinear optical effects and post-experiment correction of in-coupled photon intensity is in principle not possible or not reasonable. The QWIP experiment requires beam power stability in the order of 1 % over a few tens of ms.

FEL wavelength stability is outstandingly important at experiments using narrow bandwidth excitations or absorptions. Resonances in scanning near-field optical microscopy (SNOM) are smaller than 1% in some cases and require wavelength stability better than 0,5 % over a few hours.

Another argument for wavelength stability is the fact that some FEL experiments use water transmission windows to deliver the FEL beam to the target. Mismatched beam wavelength or spectral width can affect the beam intensity, the spectral distribution and even the temporal beam structure by modifying the spectral content of the pulse which is shown in Fig. 1.

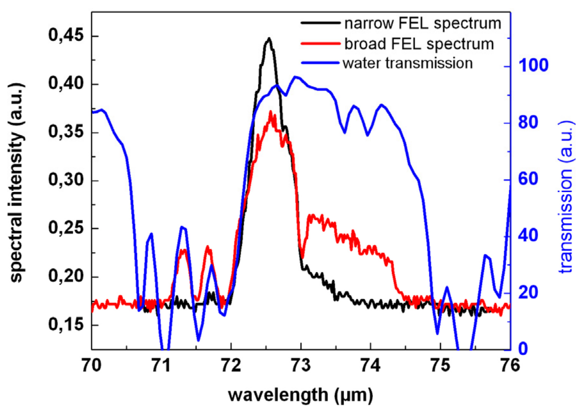

Figure 1: Spectral FEL pulse modification by water absorption windows.

BEAM POWER FLUCTUATION MEASUREMENTS

Because FEL beam power fluctuations appear in different frequency ranges the investigations split in low- (up to 1 Hz), medium- (up to 10 KHz) and high-frequency fluctuations (up to 1MHz). All investigations have been performed at the ELBE U100 FEL at 42 µm wavelength. The expected sources for low- and medium-frequency power modulations are mechanical and electrical instabilities whereas fluctuations in the high frequency range probably stem from FEL physics caused gain oscillations.

Low-frequency beam power fluctuations have been measured by continuous data logging with a NICOLETE VISION data logging system with a 10 Hz sampling rate. Fig. 2 shows a typical low-frequency FEL power signal at different detuning of the optical FEL cavity together with the horizontal beam position in the ELBE injector. This beam position correlates also with horizontal intra undulator beam position and thus with the level of overlap between electron and infrared beam. At small detuning (10 µm, high FEL gain) the FEL output varies to 4 % (peak-to-peak) and no systematic correlation between the beam position and power signal is observed. At maximum detuning of about 80 µm (small FEL gain) the situation is completely different. The relative power fluctuation level rises up to about 15 % (peak-to-peak) and correlations to the injector beam position are clearly visible. The mean amplitude of position modulation shown in Fig. 2b is very low and amounts to 100 µm. It shows that the FEL at maximum detuning is extremely sensitive to beam position instabilities. The oscillation period of about 20 seconds is probably caused by power supply drifts of injector solenoids or steering magnets. Charge collecting on beam viewer windows or other

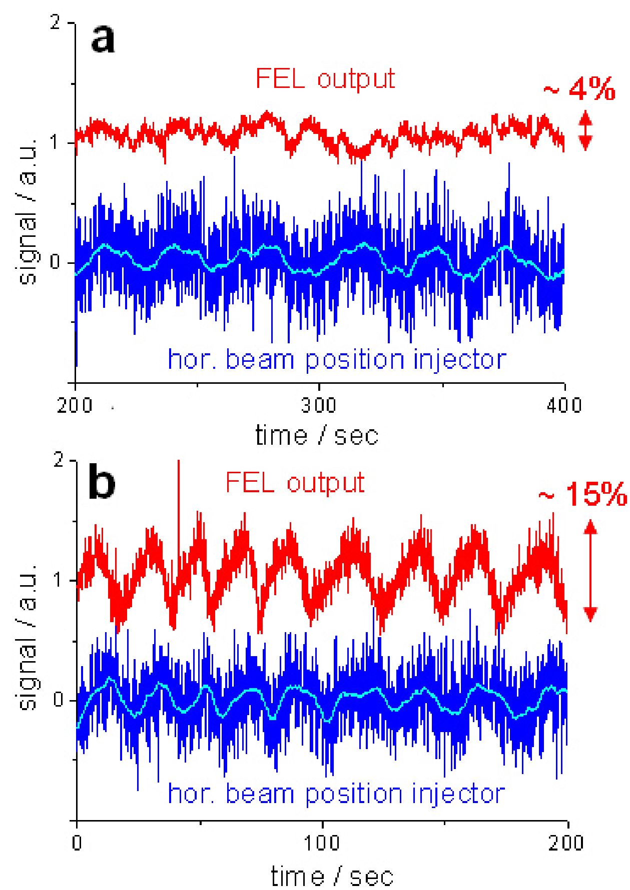

Figure 2: Low-frequency FEL power modulation in correlation with the horizontal injector beam position. a: At small FEL detunig (10 µm), b: At maximum FEL detuning (80 µm).

insolating beam line components (ceramics) can also produce slow changes of the beam position.

Medium-frequency power fluctuations were measured with a Ge:Ga detector HDL-5 (Infrared Lab) and an PC-audio card with 128k samples/s and 96 kHz frequency range at maximum. Typical beam power modulation in the low frequency range are also caused by 50 Hz hum in power supplies and 50 Hz electromagnetic fields. Fig. 3 shows typical power fluctuation spectra up to 11 kHz for different detuning of the optical cavity. The main part of fluctuations is located between 0 to 3 kHz. The fluctuations are caused by 50 Hz noise and ripples of switched power supplies. The integrated spectrum power from 0 to 3 kHz shows a significant minimum near to zero detuning. It demonstrates that the FEL operates more stable at high FEL gain. The peak at 10 kHz is caused by a small leakage current of the macro pulse generator coils in the injector. This current should be exactly zero in cw mode but because of mismatched electronic transistor stages there is a small residual current which deflects the 250 keV ELBE injector beam by a very small angle. This deflection (~100 µm deviation from beam axis at capture in ELBE Linac 1) leads to significant FEL power oscillation. This example

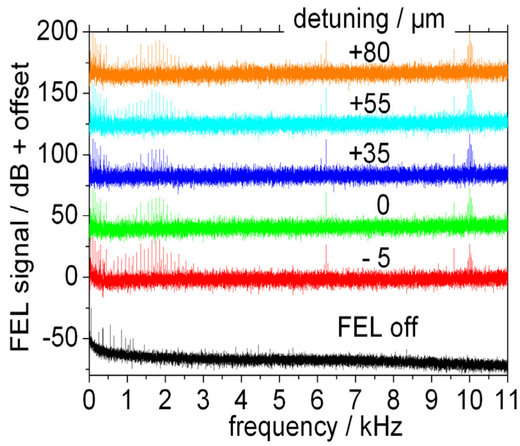

Figure 3: FEL power fluctuation spectra of U100 FEL at different detuning (0-11 kHz).

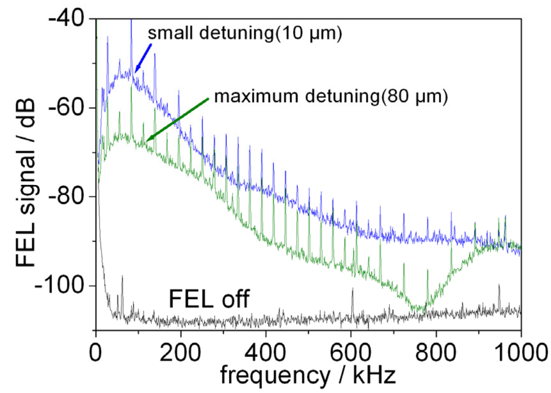

Figure 4: FEL power fluctuation spectra of U100 FEL at different detuning (0-1 MHz).

impressively demonstrates the benefit of those kinds of studies to localize non perfect operating accelerator components. It is interesting to mention that even the 15,6 kHz frequency controlling the horizontal deflection of the used Vidicon cameras (injector beam viewers) can be observed.

The high-frequency FEL power fluctuations were measured by means of a self made fast Ge:Ga detector (bandwidth ~1 MHz) and 6 GHz spectrum analyzer Agilent E4404. The measurement was done in the high magnetic field lab downstream an about 50 m long IR transfer line. The FEL was again operating at 42 µm in cw mode. Fig. 4 shows the high- frequency spectra of the detector signal at near zero detuning, maximum detuning of about 80 µm and without running the FEL. The spiky spectra lines with 25 kHz distance are an artefact and caused by the detector amplifier oscillations. The visible enhancement of the maximum detuned spectra around 900 kHz can be explained by resonant-like phenomena due to modulated desynchronism [4].

WAVELENGTH FLUCTUATION MEASUREMENTS

To determine the wavelength instabilities fast measurement of the spectral distribution of the FEL beam is needed. Fourier Transformed Infrared (FTIR) spectrometers are applicable devices for this task. Together with fast IR detectors measurement cycles of a few seconds are possible. We used BRUKER EQUINOX 55 and a MCT IR detector (ID316/8 Infra Red) for a fast determination of the FEL spectra of the U27 FEL at 11 µm in cw mode. The detector for this wavelength range is fast which reduces the measurement cycle to about 4 seconds. A set of 50 measurements was automatically stored and evaluated. Fig. 5 shows a set of spectra in a stable (a) and unstable (b) FEL regime. Stability was affected by accelerator RF cavity detuning which leads to oscillations of the electron beam energy. Wavelength and power fluctuations are observed in the unstable FEL regime. The variation of the wavelength during the 200 seconds long period of measurement is in the same order of magnitude as the line band width. As a result the average spectral line width during a long term experiment leads to a broadening by a factor of two. Furthermore a long term energy drift shifts the FEL wavelength by a few percent over a few hours. Therefore active feed-back loops for both FEL power and wavelength have been developed.

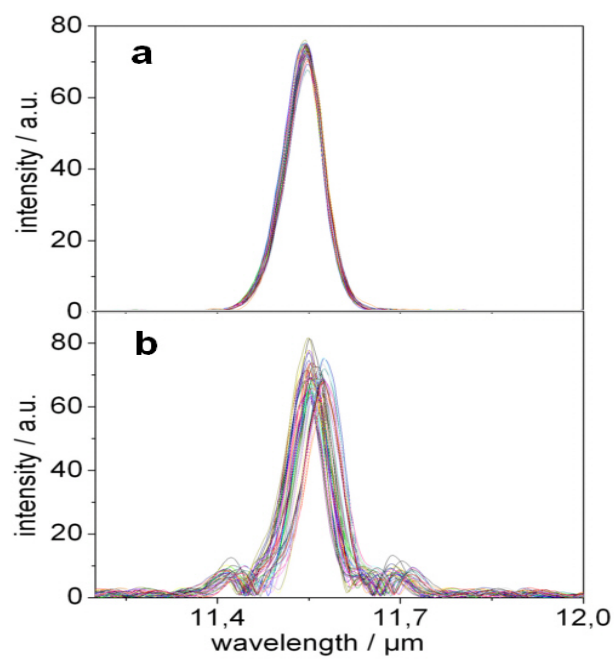

Figure 5: Sampled FEL spectra in stable (a) and unstable (b) FEL regime.

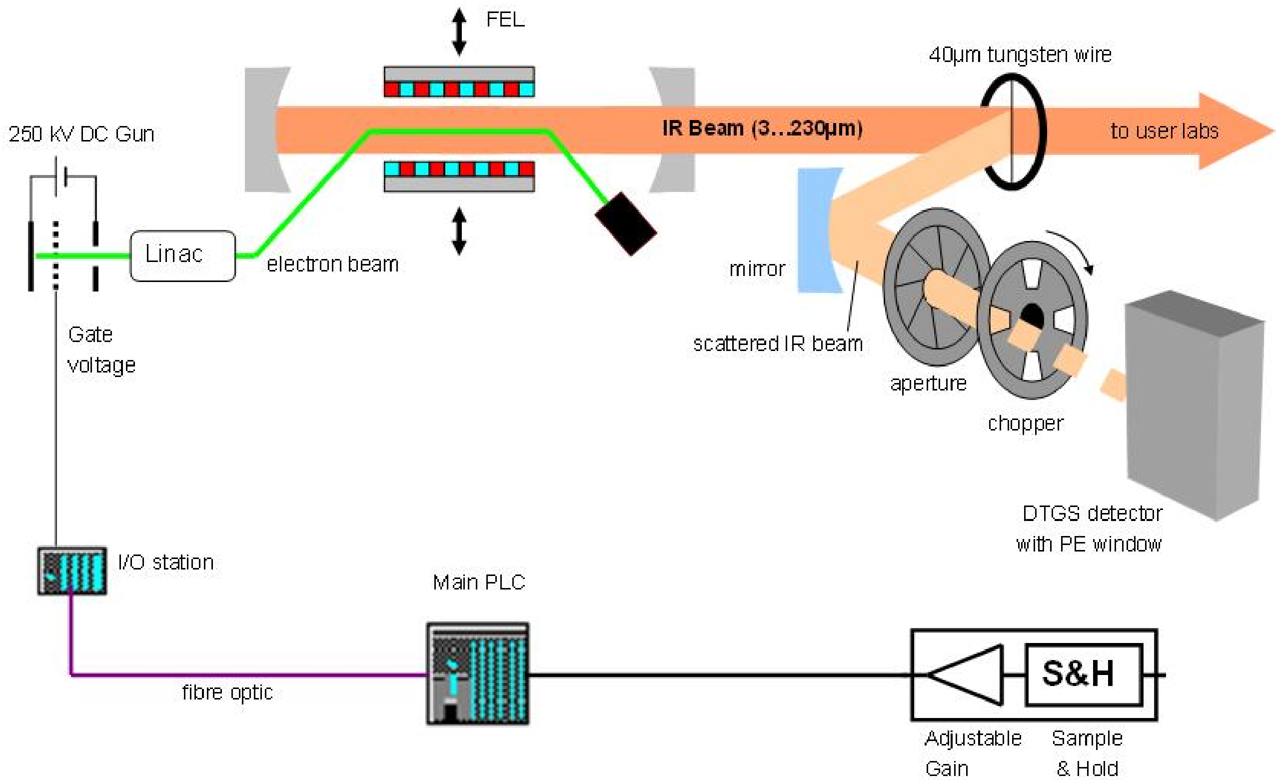

Figure 6: Feed-back system for FEL beam power stabilization.

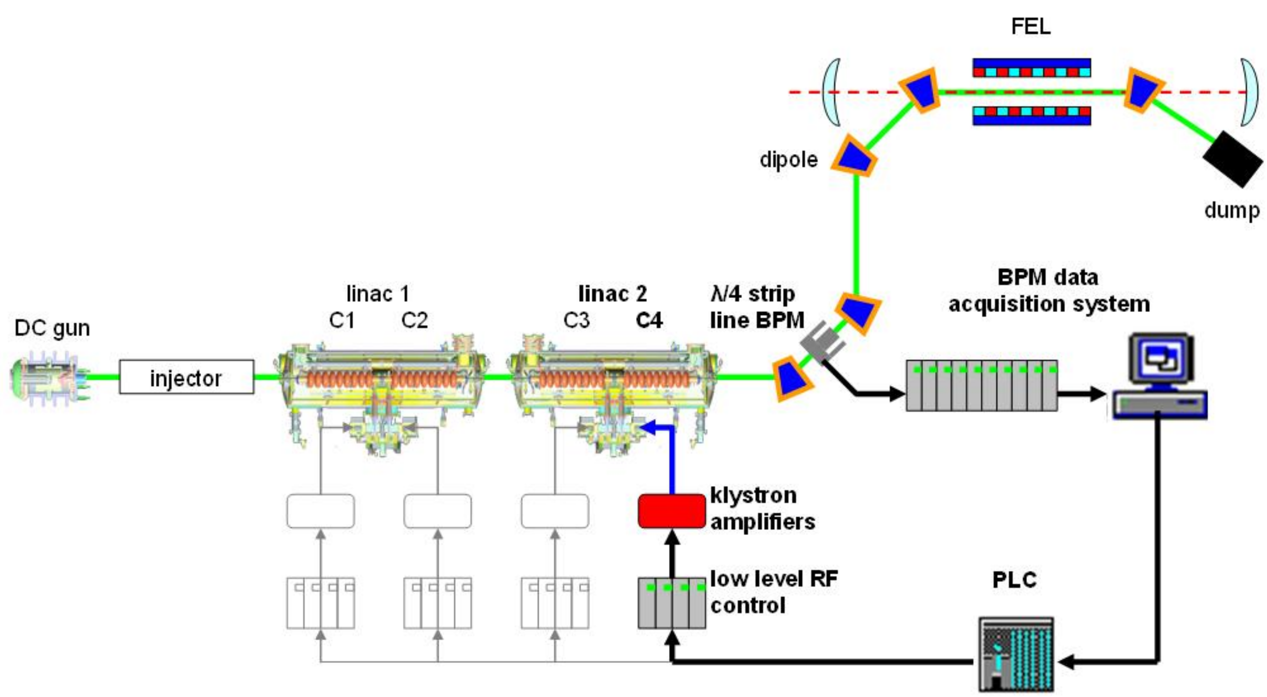

Figure 7: Feed-back system for energy (FEL wavelength) stabilization.

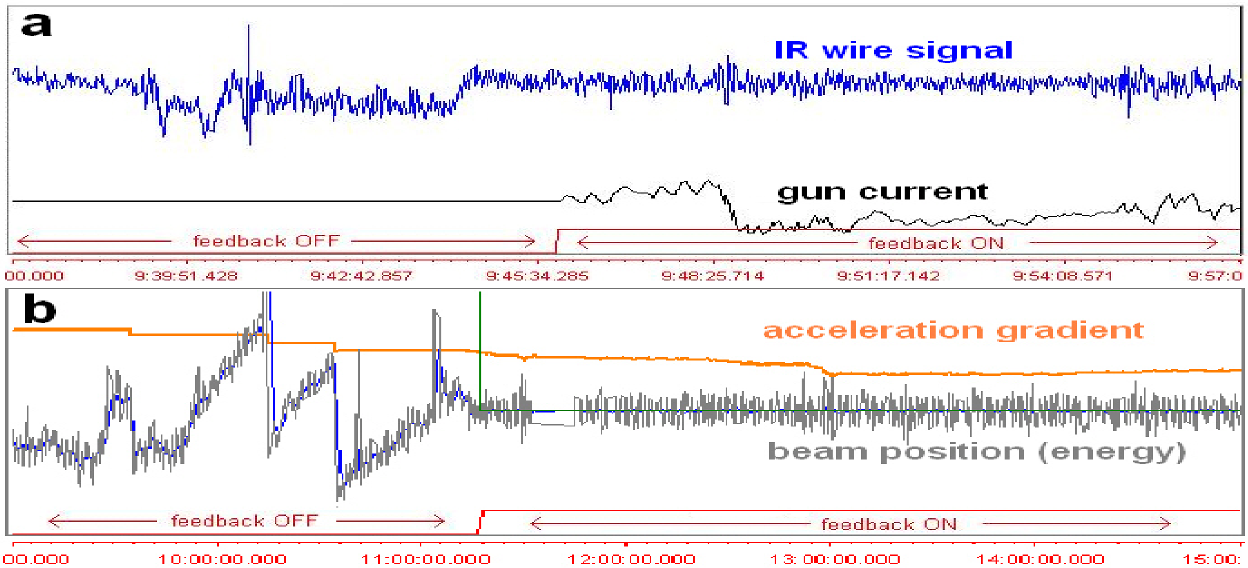

Figure 8: Effect of feedback control for FEL power (a) and FEL wavelength (electron beam energy) (b).

FEED-BACK SYSTEMS AND RESULTS

Fig. 6 and 7 show the developed feed-back systems which improve the ELBE FEL beam stability considerably. For power stabilization a small fraction of out-coupled IR beam power is deflected by a 40 µm tungsten wire into a Bruker DTGS-IR detector D210/3. A 800 Hz beam chopper is required because the detector is not sensitive to DC signals. A Simatic S7 PLC processes the detector data and delivers a PID output for controlling the main accelerator current by steering the gun grid voltage level. A calibration curve is used to control the process effectively. Because of the limited speed of the detector, chopper and control unit (PLC cycle time ~ 10 ms) the bandwidth of the scheme is limited to about 5 Hz. The feed-back for energy stabilization is also based on numerical PLC PID control. The beam position signal from a stripline monitor located in the energy dispersive beam line section is sampled in a fast PXI data acquisition system. Beam position is further given as input in a Simatic S7 PLC which calculates field gradient correction for one of the ELBE RF cavities. The control bandwidth is also limited by PLC cycle time to a few Hz. Fig. 8 shows the effects on the FEL beam power (a) and the electron beam energy (b) by using the described active control systems. The curves present logged data over time and stored by the ELBE WinCC visualisation system. In the left-hand side feed-back control is switched off and fluctuations of both FEL beam power and electron beam energy are observed. The steps in acceleration gradient curve during off-switched feed-back is due to manual energy correction by the ELBE operator and correspond to the real situation without the automatic stabilization system. After the activation of the feed-back (right-hand side) the IR beam power signal and the electron beam position in the energy dispersive beam line section stays relatively constant at least for slow corrections. It was demonstrated in real user operation that the beam stability is improved by reducing the peak-to-peak wavelength and power fluctuation by a factor of 4 and 2 respectively.

OUTLOOK

Because the present feed-back systems are not able to avoid beam fluctuations with frequencies higher than 5 Hz it is necessary to develop faster systems which in particular reduce the 50 Hz and higher harmonics influence. For that reason a FEL power feed-back system basing on a cooled Ge:Ga detector, fast control unit (RIO with FPGA, sampling time 500 µs) and fast signal transmission to the gun grid via glass fibres is under construction. The similar control unit is planned to be used for electron beam energy stabilization to eliminate the slow PLC's. The expected band width of the total system is approximately 1 kHz.

CONCLUSION

It has been shown that power and wavelength drift and fluctuation drastically affect the FEL beam stability and consequently the experimental results or efficiency. Those instabilities occur in a wide frequency range reaching from slow drifts over hours up to MHz. Detailed studies in frequency range are very helpful to localize the technical sources of instabilities and provide important information necessary for the development of active feed-back controls. Such systems have successfully been implemented at ELBE.

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