A PASS-BY-PASS GAIN MEASUREMENT TECHNIQUE FOR OSCILLATOR FELS*

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Abstract

We present a new pass-by-pass gain measurement technique for a storage ring FEL. Typically, the FEL oscillator gain is obtained by measuring the growth of the envelope of an optical macropulse using a slow photo-detector. While successfully used for low-gain FEL operation at Duke FEL laboratory for many years, this method was not adequate for measuring higher gains of distributed optical klystron FELs. We have developed a new gain measurement technique based upon the direct measurement of the micropulse energy from one pass to another using fast photo-detectors. This technique provides a powerful tool to study the entire FEL gain process, including the startup process of the FEL lasing. In this work, we describe this new gain measurement technique in detail and compare it with the old technique. Using fast photo-detectors with a picosecond time response, this new technique can be extended to measure the gain of other oscillator FELs, including those driven by superconducting linacs.

DUKE FEL/HIGS FACILITY

The Duke Free-Electron Laser Laboratory (DFELL) operates several accelerator based photon sources including the UV-VUV storage ring FEL and an FEL driven Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS) [2]. The DFELL accelerator facility is comprised of three accelerators, the linear accelerator pre-injector (linac), a full-energy, top-off booster synchrotron, and a 0.18 – 1.2 GeV electron storage ring. A set of key operation parameters for the booster and storage ring are summarized in Table 1.

Table 1: Parameters of DFELL accelerators.

	Storage ring	Booster
Maximum energy [GeV]	1.2	
Injection energy [GeV]	0.18-1.2	0.18
Beam current [mA] single/multi-bunch	100/300	3/5
Circumference [m]	107.46	31.902
Revolution frequency [MHz]	2.79	9.397
RF frequency [MHz]	178.55	

Designed as a dedicated FEL drive, the Duke storage ring hosts several free-electron lasers in a thirty-four meter long FEL straight section. A planar optical-klystron FEL, the OK-4 FEL, consists of two planar wigglers sandwiching a bunch magnet. A helical FEL, the OK-5 FEL, is comprised of two helical wigglers separated by more than 20 meters. Operating four wigglers together, two OK-4 and two OK-5 wigglers, we demonstrated in 2005 the lasing of world's first distributed optical klystron FEL, the DOK-1 FEL [1]. Both the OK-4 and OK-5 wigglers were developed and built in Budker Institute for Nuclear Physics (BINP); a set of wiggler parameters are provided in Table 2.

Table 2: Parameters of Duke FEL wigglers

	OK-4	OK-5
Polarization	Horizontal	Circular
No of wigglers	2	2 installed
No of regular periods	33	30
Wiggler periods [cm]	10	12
Peak field [kG @ 3kA]	5.36	2.86
FEL wavelength [nm]	193 - 2000	

The gain measurement is critical for the study of the FELs and for optimizing the FEL performance for light source user applications. At the DFELL, for many years, the FEL gain was obtained either directly by measuring the build-up of an FEL macropulse envelope with a slow photon detector or indirectly by measuring the threshold FEL lasing against the cavity loss curve. While useful, both methods have difficulties in measuring relatively high-gain operation of the storage ring FELs, in particular, the DOK-1 FEL. In this work, we present a new gain measurement technique based upon the measurement of the build-up of individual micropulses. This method is very versatile, applicable to both low gain and higher gain regions and has recently been extended to study the FEL process from noise to saturation, expanding more than five decades of power increase.

PHOTO-DETECTORS FOR GAIN/LOSS MEASUREMENTS

The gain of a storage ring FEL can be determined by measuring the growth rate of the FEL optical power which is built up over many passes of the FEL resonator. A precise measurement of the energy of individual micropulses from pass to pass remains challenging. For example, when the Duke storage ring is operated in a single-bunch mode, the optical micropulses with a typical duration of hundreds of picoseconds are separated by about 360 ns from one pass to another. A pass-by-pass optical power measurement requires the use of photo-detectors with the following properties: (1) a fast time response of few ns to 50 ns; (2) a linear amplitude response to the micropulse power (linearity); and (3) a low level of noise. In practice, we used reasonably fast

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photo-detectors, namely silicon pin photodiodes and photomultiplier tubes (PMTs), with a response time of ~1.5 ns and ~15 ns respectively (see Table 3). The fast response gave us flexibility to use either a numerical or an analog filtering in the signal/data processing.

Table 3: Parameters of photo-detectors.

Silicon PIN photodiodes ET2020 (Vendor: Electro-Optic Technology):	
Sensitivity	0.5 A/W
Bias voltage	30 V
Cut off frequency	200 MHz @50 Ohm
Rise time	< 1.5 nS
Noise equivalent power (NEP)	< 1 pW/sqrt(Hz)
Active area	2.55 mm dia
Photomultiplier R928 (Vendor: Hamamatsu):	
Wavelength range	185-900 nm
Cathode sensitivity	74 mA/W
Pulse response	13-15 nS
Equivalent noise input (ENI)	$1.3*10^{-16}$ W/sqrt(Hz)
Gain at 500 V anode voltage	10^5
Gain at 1000 V anode voltage	10^7
Amplifier for photodiodes:	
Transimpedance gain	10^5 @50 Ohm load
Transimpedance bandwidth	10 MHz
Max output voltage	2 V @50 Ohm load
Dark offset	< 1 mV

The detector signals need to be matched to a realtime multi-GHz digital oscilloscope, in our case, a LeCroy WP7100A oscilloscope with a 1 GHz analog bandwidth. For the purpose of additional noise suppression, we used an internal 20 MHz bandwidth filter in all four channels of the oscilloscope. Because the same oscilloscope is used for measuring the energy growth of FEL mircopulses over several decades, a multi-stage system with several detectors have been developed. To measure the detector signals in parallel, the output of each detector is optimally matched to the sensitivity range of the oscilloscope. In a typical setup, the low level optical signals, including spontaneous radiation signals, are measured using a highly sensitive Hamamatsu PMT. To avoid the impact of shot noise caused by a single electron, the anode voltage of the PMT is limited to below 600 V. As the FEL signal grows, the higher level signal is measured using a silicon pin photodiode. The optical signal is properly attenuated so that the photodiode output can be matched to that of a PMT in order to be captured by the same oscilloscope. One photo-detector can cover a dynamic range of up to 200 with a linearity of about 1-2 bits or better.

PASS-BY-PASS GAIN MEASUREMENTS

A technique to measure the FEL gain using a fast steering magnet (a gain modulator) and a photo-detector was developed many years ago at the DFELL [3]. Typically, a single and relatively slow photodiode was used to measure the envelope of an FEL macropulse. The FEL macropulse gradually built up as the electron beam was returned to the lasing orbit to interact with the FEL optical beam following the ramp-down of the magnetic field in the fast steering magnet. While working reasonably well for the low gain operation of the OK-4 FEL (up to ~10 %), this technique was found to be inadequate for measuring FEL gains higher than about 15-20 % per pass.

After installation of two additional OK-5 wigglers in 2005, the first distributed optical klystron FEL in the world, the DOK-1 FEL, was brought to operation [1]. The DOK-1 FEL includes two planar OK-4 wigglers, two helical OK-5 wigglers and three buncher magnets. The DOK-1 FEL set a FEL gain record for storage ring based FELs at about 48% per pass as reported in [1]. To measure a higher FEL gain, a pass-by-pass gain measurement technique using a photomultiplier tube was developed in 2005. Fig. 1 shows the growth of an optical macropulse obtained by a slow photodiode by measuring the macropulse envolope and by a faster PMT by recording the growth of individual micropulses. Compared with the envelope method, the pass-by-pass technique allows us to effectively deal with the fast varying noise background during the macropulse. The noise background is calculated as a sequence of "instantaneous" zero-offsets for individual FEL micropulses. The offset is then subtracted from the fitting of a specific micropulse.

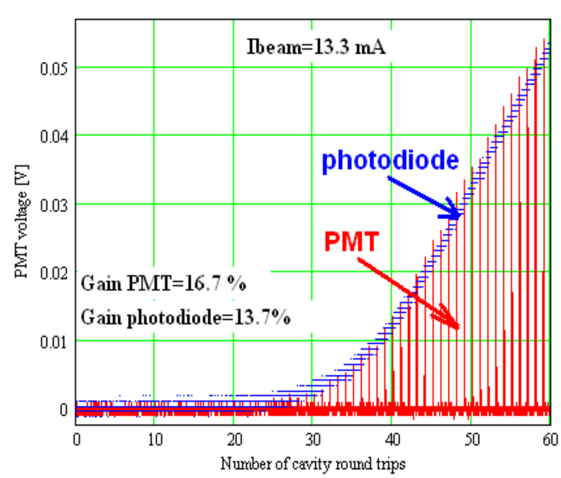

Figure 1: Comparison of two FEL gain measurement techniques. The same FEL macropulse is captured by a slow photodiode (blue) and by a fast PMT capable of measuring the optical power pass-by-pass (red). The FEL configuration is the DOK-1 FEL operating at 450 nm with a 600 MeV electron beam and a single bunch current of 13.3 mA.

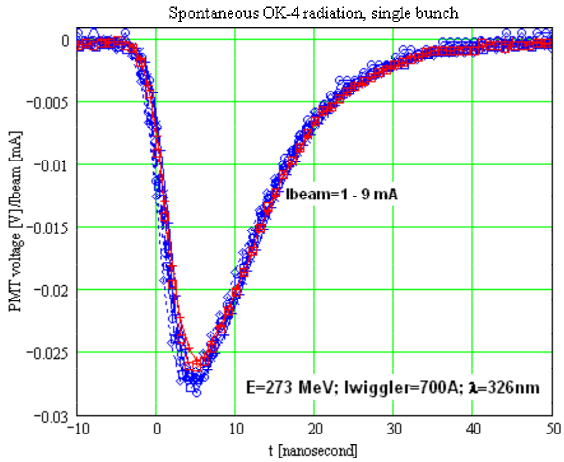

Figure 2: Typical PMT responses and the linearity check. The OK-4 wiggler spontaneous radiation is measured with a 270 MeV electron beam at 326 nm. The beam current is varied from 1 to 9 mA with the RMS duration of micropulses varying from 40 to 90 ps. The measured PMT signal is normalized by the beam current to check the linearity. The PMT pulse is fit to a function, $U_{PMT}(t)=A\cdot(\tanh[(t-t_1)/\tau_1]+1)(\tanh[(t_1-\Delta t-t)/\tau_2]+1)$, where A and t_1 are the variables of the fit, and τ_1, τ_2, and Δt are fixed for all pulses.

With the DOK-1 FEL gain as high as 30-50% per pass, it took only 6 – 9 passes for the optical pulse to grow by a factor of ten. Therefore, with the resolution of an oscilloscope limited by 8 bits, one PMT could only capture twenty or fewer data points in the exponential region of the macropulse. In a single-stage system, a compromise was made to capture part of the exponential growth for gain determination and part of the initial saturation region to illustrate the reduction of the gain due to saturation (see Fig.4 and 5). The FEL gain results reported in [1] were obtained using this method.

Recognizing the limitation of a single-stage system, we started to develop a multi-stage measurement system in 2005. A number of photo-detectors, including PMTs and photodiodes, were purchased and evaluated. In 2007, we finalized a multi-stage FEL gain measurement system with three or four photo-detectors to cover different stages of the macropulse development. With this system, we can now study the entire FEL process, starting from the spontaneous wiggler radiation, to initial accumulation of optical power in the non-exponential growth region, to exponential growth, and finally to saturation and decay of the optical power.

MULTI-STAGE GAIN MEASUREMENTS

A photo of four-stage FEL gain measurement bench is shown on Fig.3. The number of stages, and therefore, photo-detectors, is limited by the maximum number of the oscilloscope channels which can acquire data simultaneously. The optical radiation out-coupled from the FEL optical cavity is split between the stages. In the first and most sensitive stage we use Hamamatsu PMT R928 (see Table 3), receiving the optical pulse after passing through a monochromator. The monochromator serves as a wavelength filter with a wavelength bandwidth of 0.3–3.2 nm. The other three stages receive full bandwidth of out-coupled FEL radiation, collimated by a diaphragm with an opening radius about two to three sigmas (2 to 3 σs) of the TEM_{00} FEL mode. In all stages, low-loss optical lenses are used to transport the optical beam onto the sensitive area of the detectors. In the higher signal region, the stage #4, a lower-sensitivity detector, an ET2020 pin photodiode, is used (Table 3). In the intermediate stage #3, either a pin photodiode with an amplifier or a PMT can be used (see Fig. 3). A portion of the out-coupled optical power received by each detector is attenuated using a number of neutral density filters. For a fine tuning of sensitivity of the PMTs we vary the PMT voltage within a small range of 500±70V.

The sensitivity of each stage can be tuned for a specific segment of the FEL macropulse. For the gain measurements, the detectors are usually tuned in order to cover the entire range of the FEL power growth (5-6 decades) with some overlap.

Figure 3: (Upper photo): a four-stage FEL gain measurement bench with two photodiodes and two PMTs. (Lower photos): the 1st stage PMT receives the optical beam after a monochromator with its exit slit opened to about 3.2 nm.

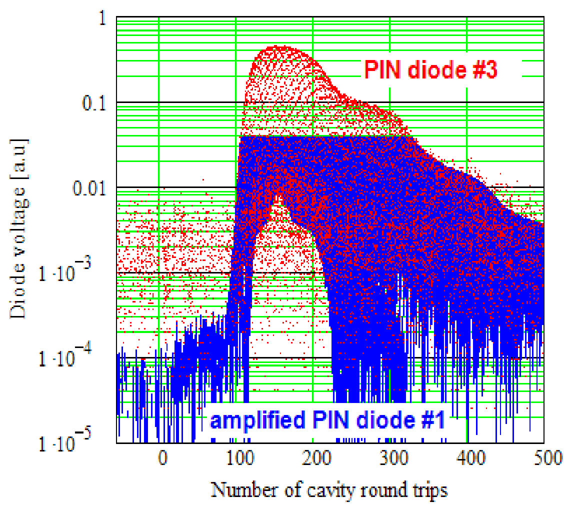

Figure 4: An FEL macropulse obtained by a three-stage photodiode system. The FEL configuration is the DOK-1 FEL with a 600 MeV, 16.7 mA single-bunch electron beam lasing at 383 nm. The measured net gain is about 35% and the total gain is about 39%.

Fig.5 presents an example of such measurements. The monochromator of the first stage has to be accurately tuned to the lasing wavelength. The sensitivity of the PMT#1 is adjusted to capture the optical pulses of the initial spontaneous wiggler radiation with a resolution of 3-5 bits. However, this early stage can be re-tuned to a higher sensitivity for more detailed study of the initial optical power growth and radiation bandwidth narrowing. For example, in an earlier measurement with a three-stage setup (Fig.4), the first stage employed an amplified photodiode to capture the transitional, non-exponential growth of the optical macropulse preceding the exponential rise.

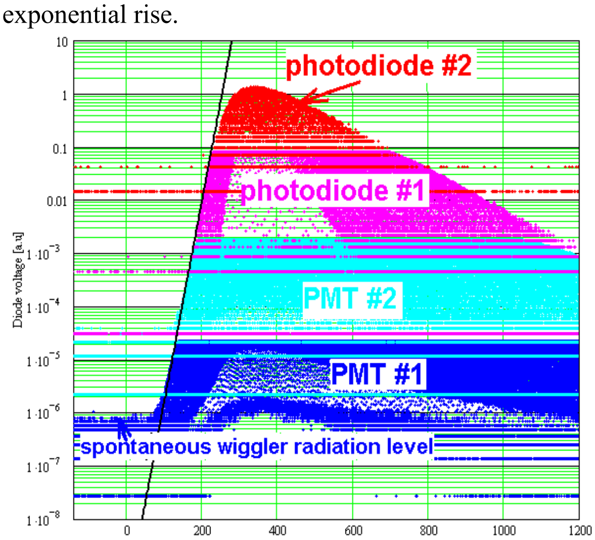

Figure 5: An FEL macropulse obtained by a four-stage measurement system. The FEL configuration is the OK-4 FEL with a 600 MeV, 15.7 mA single-bunch electron beam. The measured net gain is about 8.6% and the total gain is about 9.2%.

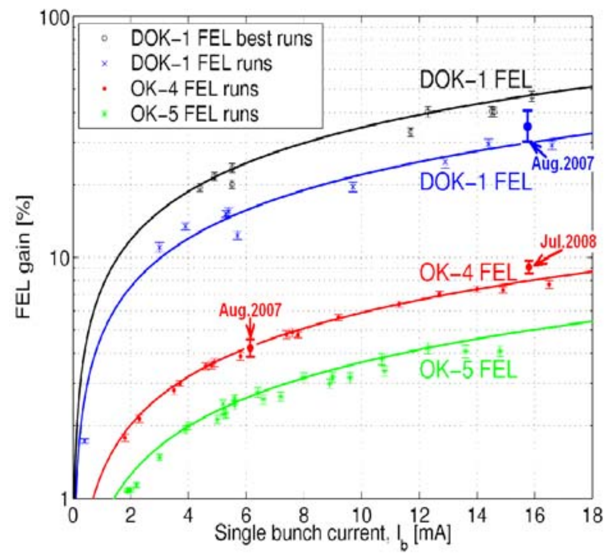

Figure 6: The FEL start-up gain measured for different wiggler configurations. The fit curves show the gain vs. beam current dependency Gain~$I_{beam}^{2/3}$. The data of 2005 pass-by-pass measurements is reported in [1]. Three 2007 and 2008 measurements using a multi-stage system are added.

The measured FEL gain results in 2007 and 2008 were compared in Fig. 6 with the 2005 gain results as reported in [1]. The 2005 gain data were taken with a single-stage PMT system to capture part of exponential growth region and part of the saturation region. The 2007 and 2008 data were taken with a multi-stage measurement system to capture the entire growth process of the FEL macropulse from noise to saturation. Fig. 6. shows a good agreement of FEL gain data from 2005 to 2008.

CONCLUSION

The pass-by-pass FEL gain measurement system based upon a multi-stage optical bench has proven to be a versatile tool for study of the FEL physics. It can be applied to both low gain and higher gain regions of the storage ring FEL operation. In addition, this system has been used to measure the FEL cavity losses. Using fast photo-detectors with a picosecond time response, this technique can be used for other types of FEL oscillators, including the high-power FELs driven by superconducting linacs.

REFERENCES

[1] Y. K .Wu, N. A. Vinokurov, S. Mikhailov, J. Li and V. Popov., Phys. Rev. Lett. 96, 224801 (2006)

[2] H. R. Weller, *et al.* "Research Opportunities at the Upgraded HIγS Facility," an invited review article for Prog. Part. Nucl. Phys. (2008).

[3] I. V. Pinaev *et al.*, Nucl. Instr. and Meth. A 475 (2001), pp. 222-228 (2001).