PASS-BY-PASS MULTISTAGE FEL GAIN MEASUREMENT TECHNIQUE FOR A STORAGE RING FEL*

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Abstract

This paper presents a novel technique of measuring the gain of a storage ring based FEL oscillator. As opposed to the conventional technique of measuring the FEL gain from its macro-pulse envelope, this new technique is based upon the measurement of pass-by-pass FEL micro pulses. To record the growth of the optical energy in the FEL micro-pulse train, we use fast photo-diodes and photo-multiplier tubes (PMTs). PMTs are usually employed at the very beginning of the FEL lasing development, while the photodiodes are used at the latter stages when the FEL power is fully developed and saturated. This new gain measurement technique provides a powerful tool to study the details of the FEL gain process starting from spontaneous radiation to saturation. It allows us to investigate five to seven orders of magnitude of the FEL energy growth. As fast photo-detectors with a sub-nanosecond time response become available, this new technique can be adopted for other oscillator FELs, including those driven by super-conducting linacs. Special attention is paid to the dynamic non-linearity issues of the photodiodes and PMTs associated with short FEL pulses.

DUKE FEL/HIγS 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 (HIγS) [2]. The DFELL accelerator facility includes 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. Main parameters of the booster and storage ring are listed 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].

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 five to seven decades of power increase.

PHOTO-DETECTORS FOR GAIN AND 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. A pass-by-pass optical power measurement requires the use of photo-detectors with (1) a fast time response of few ns to 10 ns; (2) a linear amplitude response to the micropulse power (linearity); and (3) a low level of noise. We used silicon pin photodiodes and photomultiplier tubes (PMTs), with a response time of ~1.5 ns and ~15 ns respectively (see Table 3).

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

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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

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 a range of several decades, a multi-stage system with several detectors has 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. 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 0.5-1.0 %.

PASS-BY-PASS GAIN MEASUREMENT

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]. 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. Before the installation of additional OK-5 wigglers and commissioning of the first distributed optical klystron FEL (DOK-1) in 2005 [1], a typical range of the FEL gain was up to 15 %. A slow photodiode with additional integrating amplifier was used to measure the envelope of an FEL macropulse [3]. With the DOK-1 brought to operation, we had to measure FEL gains in the 30-50% range. The DOK-1 FEL set a FEL gain record for storage ring based FELs at about 48% per pass as reported in [1]. With that gain level, we found out that we could not use a slow photo-sensor [4]. To measure such gain, we developed a pass-by-pass gain measurement technique using PMT's and fast photodiodes see (Table 3).

With a gain of 30-50%, 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 sensor could only capture twenty or fewer micropulses 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 (Figure 2). Recognizing the limitation of a single-stage system, we developped 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

Figure 1 shows a photo of four-stage FEL gain measurement bench. 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, 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 the out-coupled FEL radiation, collimated by a diaphragm with an opening radius about 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. In the intermediate stage #3, either a pin photodiode with an amplifier or a PMT can be used. 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 to cover the entire range of the FEL power growth of 5-6 decades with some overlap. Figure 2 presents an example of an FEL macropulse measured on the bench. 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.

Figure 1: A four-stage FEL gain measurement bench with two photodiodes and two PMTs. On the right: the 1st stage PMT receives the optical beam after a monochromator with the exit slit opened to about 3.2 nm.

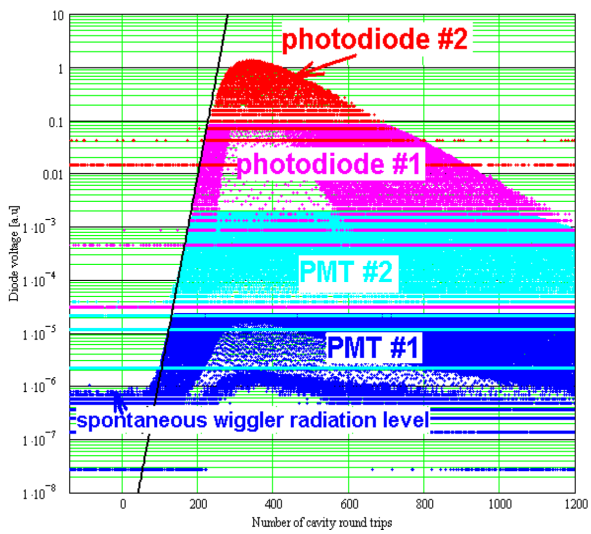

Figure 2: An FEL macropulse obtained by a four-stage measurement system. The OK-4 FEL with a 600 MeV, 15.7 mA single-bunch electron beam. The measured net gain is about 8.6% and the total gain is about 9.2%.

LINEARITY RANGE OF PHOTOSENSORS WITH ULTRA SHORT OPTICAL PULSES

The most challenging effect which might ultimately limit the accuracy of the gain measurement is dynamic non-linearity of photo sensors. This is a specific non-linear response to optical pulse with a duration of 10^{-13}–10^{-9} sec. It is noticed that the voltage range of biased photodiodes required for ~0.1-1% linearity, which is ~1 V for slow (0-10 kHz) optical signals, drops down to 30-50 mV for our FEL optical pulses. Sensitivity of the photodiodes in the linear range remains constant. For the pulse magnitude above 50-100 mV, saturation of photodiodes shows up in pulse widening. This non-linearity is also clearly observed using optical neutral density filters with known attenuation. Similar effects might also exist in PMT's. The nature of the effect of saturation of the photo-sensors by ultra short optical pulses at very low voltage levels needs further investigation

Thus, the linearity range must be tested for any specific photo-sensor with particular width range of optical pulses Figure 3 demonstrates a method we used to prove the linearity range of a photo-sensor. It employed spontaneous wiggler radiation with pulse magnitude proportional to the electron beam current. The accuracy of this method, limited by the resolution of the oscilloscope and noise of beam current measurement, was ~1%. The non-linearity of the PMT (Figure 4) was ~2-3%.

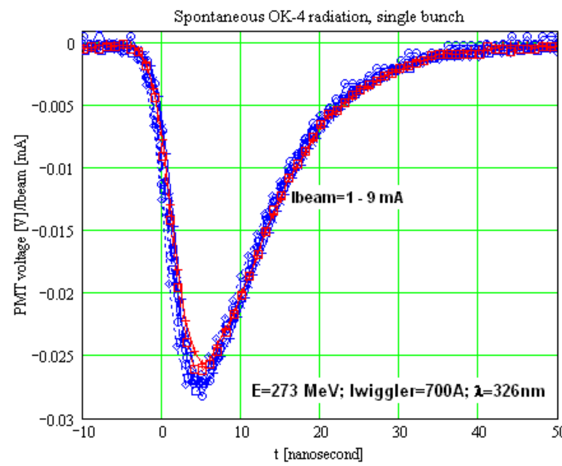

Figure 3: Typical PMT responses and the linearity check. The OK-4 wiggler spontaneous radiation is measured with a 270 MeV electron beam at 326 nm. The beam current is varied from 1 to 9 mA with the RMS duration of micropulses varying from 40 to 90 ps. The measured PMT signal is normalized by the beam current to check the linearity.

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. This system is also 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. The dynamic non-linearity effects of the photo-sensors with ultra short optical pulses are under further investigation.

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