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# AN INVESTIGATION OF POSSIBLE NON-STANDARD PHOTON STATISTICS IN A FREE-ELECTRON LASER I: EXPERIMENT

Jeong-Wan Park*, University of Hawaii at Manoa, Honolulu, U.S.
Kwang-Je Kim[1], Ryan Lindberg, Argonne National Laboratory, Lemont, U.S.
[1]also at University of Chicago, Chicago, U.S.

*Abstract*

It was reported that the photon statistics of the seventh coherent spontaneous harmonic radiation of the MARK III FEL was sub-Poissonian [1], which concludes that Fano factor $F$ (the ratio of photon number variance to the average photon number) is less than unity. Whether FEL light exhibits such non-standard behavior is an important issue; if it does, our understanding of the FEL needs to be radically modified. In this paper, we re-examine the analyses of experimental data in Ref. [1]. We find that the observed value of $F$ could be explained within the standard FEL theory if one combines the detector dead time effect with photon clustering arising from the FEL gain. We propose an improved experiment for a more definitive measurement of the FEL photon statistics.

## INTRODUCTION

In an experiment performed some time ago by Chen and Madey [1], it was reported that the photon statistics of the seventh coherent spontaneous harmonic radiation (CSHR) of the MARK III infrared (IR) free-electron laser (FEL) was sub-Poissonian–neither Poissonian as expected from a coherent FEL output nor chaotic as expected from an incoherent radiation source. If FEL light exhibits such non-standard behavior, our understanding of the FEL needs to be radically modified. In this paper we present a re-examination of the data analysis by Chen and Madey. In the companion paper [2], we study theoretical basis for the non-standard FEL photon statistics.

## SET-UP OF THE EXPERIMENT

The Chen-Madey experiment was made at the MARK III FEL [3] operating at a fundamental IR wavelength of 2.68 $\mu$m; further parameters are presented in Table 1. The photon counting measurements used the seventh harmonic at 382 nm where high efficiency photo-multiplier tubes (PMTs) are available, since a poor efficiency PMT typically emphasizes the statistics of the measurement itself, resulting in a Possion distribution irrespective of the statistics of the source [1, 4]. In classical terms, the coherent spontaneous harmonic radiation (CSHR) is produced by the nonlinear components of the wiggle motion in the undulator, and enhanced by the seventh harmonic component of the electron current that occurs as the fundamental mode approaches the oscillator saturation [1].

* jwpark@hawaii.edu

Table 1: MARK III FEL Specification

| Parameters | Value | Unit |
|---|---|---|
| $K$ (undulator parameter) | 1.13 | |
| $\lambda_u$ (undulator period) | 2.3 | cm |
| $\lambda_1$ (fundamental mode wavelength) | 2.68 | $\mu m$ |
| Macropulse length | 2 | $\mu$s |
| Macropulse repetition rate | 15 | Hz |
| Micropulse length | 2 | ps |
| Micropulse repetition rate | 2.856 | GHz |
| Average electron beam energy | 43.5 | MeV |
| Energy spread (FWHM) | 0.4% | |
| Peak micropulse current | 30 | A |

The set-up of Chen-Madey experiment is shown in Fig. 1. The output FEL light from the cavity passed through an aperture and then a lens before it reached a dichroic beam splitter that transmitted the fundamental mode and reflected the CSHR. The beam line for the CSHR consisted of a monochrometer, an adjustable slit, a fast, high quantum efficiency PMT, and an amplifier. The CSHR was brought to a focus at the adjustable slit and monochromator combination; the former was used to adjust the count rate, while the latter selected the 7$^{th}$ harmonic. Since the slit was at the focal plane of the lens, its size defined the effective optical mode waist of the measured seventh CSHR photons.

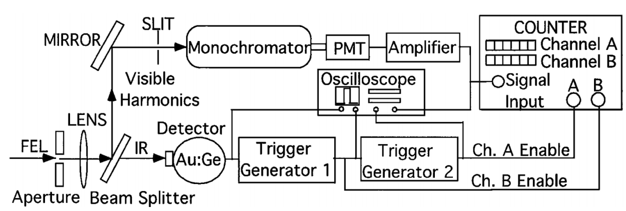

Figure 1: Diagram of photon counting experiment of the seventh CSHR from Mark III FEL [1].

Measurements of the CSHR were triggered by the signal of the IR fundamental which is measured by a fast Au:Ge IR detector. A start signal was sent to the counter by trigger generator 1 when the amplitude of the IR detector reaches a pre-set voltage, followed by an end signal after 80 ns. During the 80 ns time window the counter records the number of 7$^{th}$ harmonic pulses from the PMT along channel B. In addition, trigger generator 2 enables channel A of the counter to record the number of background photons.

The linac delivered about 230 electron bunches within each 80 ns observation window which corresponds to about 6

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cavity round-trip times. There are on average 19.5 radiation pulses at the fundamental circulating in the cavity while the macropulse is on. The wholly classical fluctuations of these bunches is diminished to the extent that each group of 230 bunches can be considered as the indistinguishable members of an ensemble. Emission into the seventh harmonic is low, so that on average the PMT measures ≤ 3 photons during any single 80 ns time window.

The goal of the measurement was the Fano factor $F$, defined by the ratio of the photon number variance to its mean,

$$F = \langle(\delta n)^2\rangle / \langle n \rangle. \tag{1}$$

Poisson statistics has $F = 1$, $F > 1$ is super-Poissonian, while $F < 1$ signifies a sub-Poissonian source that cannot be described by classical means.

## DEAD TIME OF THE COUNTER AND OBSERVED PHOTON STATISTICS

The dead time is the recovery time of a counter during which it cannot react to any photoelectron pulse. It is well-known that the dead time reduces the measured Fano factor when it becomes comparable to the inverse of the average count rate. This can be understood by considering the extreme case where the count rate is much larger than the inverse of the dead time. In this case the counter measures a photon right after every time it recovers, the count rate become uniform and equal to the inverse of the dead time, and the variance approaches zero ($F \longrightarrow 0$). Hence, the reduction of the measured Fano factor for a fixed dead time becomes more significant as the count rate increases.

Furthermore, the degree to which dead time affects the measured $F$ at a fixed count rate will also depend upon the details of the emission process. For example, photon clustering during the observation window results in an additional reduction of measured Fano factor below that of Poisson source with a constant emission rate [5]. Such photon clustering may occur in the Chen-Madey experiment if the emission probability of the CSHR increases due to FEL gain. Hence, one must consider the possibility that nonlinear bunching at the seventh harmonic could increase the CSHR during the measurement time window, which in turn would suppress $F$ beyond that predicted from dead time alone.

## RESULT OF THE EXPERIMENT

The result of Chen-Madey experiment is shown in Fig. 2. The dashed line for the theoretical dead time-modified-Poisson-radiation (DTMPR) assumes a Poisson source with 6.3 ns dead time, which was obtained from separate measurements of a LED source. The solid line fit to the observed Fano factor of the unattenuated seventh CSHR is noticeably lower than the DTMPR as shown in Fig. 2. For this reason, Chen and Madey claimed to have observed sub-Poissonian statistics in the FEL seventh CSHR (the attenuated results of Fig. 2 are irrelevant here).

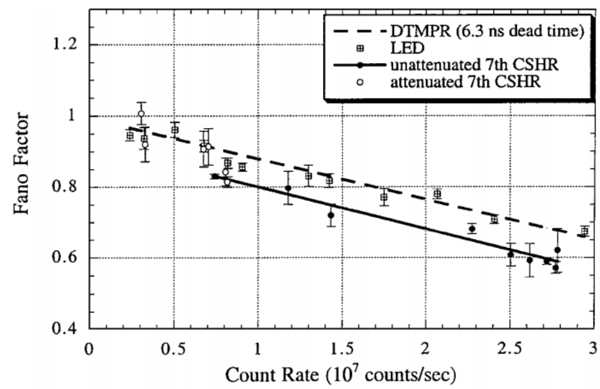


Figure 2: Result of the Chen-Madey experiment [1].

Chen and Madey also measured the auto-correlation function of the PMT voltage defined by [6]

$$G(\tau) \equiv T^{-1} \int_0^T dt\, V(t)V(t+\tau). \tag{2}$$

They expected that any photon clustering due to FEL gain would result in an enhancement of the auto-correlation function at the cavity round-trip time. Instead, the auto-correlation function displayed a local minimum at the cavity round-trip time, and Chen and Madey concluded that photon clustering could not be present. However, even if the emission is a random Poisson process with intensity increasing at each cavity round-trip, the number of photons within the observation window (normally two or three) is too little to reveal the increase faithfully through the auto-correlation function. This has been verified by our simulations, implying that their auto-correlation function study cannot rule out photon clustering within the observation window.

## SIMULATION OF THE PHOTON STATISTICS

As mentioned in the previous section, the influence of photon clustering on the measured Fano factor should be studied in more detail before definite conclusions regarding the $F$ at the source can be made. Since the Mark III FEL is no longer available to repeat the experiment, we have simulated Chen-Madey experiment using GINGER [7], and used the predicted output power at the seventh harmonic to set the (potentially time-varying) Poisson rate for the CSHR. Hence, we ignored the chaotic light nature of any given pulse, which should be an appropriate assumption since there is on average 0.05 photons within a coherence length.

The steps of the simulation are:

1. Use GINGER to determine the FEL power in the fundamental and seventh harmonic as a function of the pass number.

2. Determine the starting time (pass number) of the 80 ns time window by using the experimentally measured ratio of the power in the fundamental at the start to that in saturation.

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Table 2: Possibility That the Data Can Be Explained by the Standard FEL Thoery, Depending on the Starting Cavity Round-Trip Number of the Observation Window. NP: Non-Paralyzable Daed Time, P: Paralyzable Dead Time. ◯: Consistent, △: Approximately Consistent, ×: Inconsistent.

| Starting number | 54 | | 55 | | 56 | | 57 | | 58 | | 59 | | 60 | | 61 | | 64 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dead time type | NP | P | NP | P | NP | P | NP | P | NP | P | NP | P | NP | P | NP | P | NP | P |
| Fano factor | × | × | × | × | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | × | △ | × | × | × | × | × | × |
| Auto-correlation | × | | × | | × | | × | | △ | | ◯ | | ◯ | | ◯ | | ◯ | |

3. Determine the seventh harmonic power during the 80 ns window determined in step 2 to set the emission probability, and simulate the measurement including dead time.

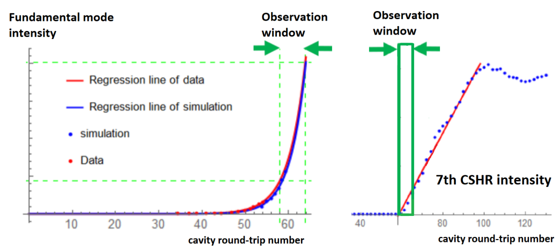


Figure 3: Simulated radiation field intensity.

The procedure of step 2 is shown in the left-hand plot of Fig. 3, where we show that the best best fit of the experiment to simulation implies that the observation window begins at GINGER round trip number 58. The right-hand plot of Fig. 3 shows the GINGER prediction of the 7th harmonic intensity profile during the same 80 ns.

In Fig. 4 we show the Fano factors of the 7th harmonic CSHR data obtained by Chen and Madey and the simulated Fano factors for two different dead time models, *paralyzable* and *non-paralyzable*. In the non-paralyzable (NP) model the counter is rendered "dead" for one dead time after a count, while in the paralyzable (P) model any photon that arrives when the counter is dead is not counted and extends the dead time by another unit; real counters typically live between these two extremes. It is seen that simulated Fano factors are consistent with the measured one. Hence, we have found by clustering the photons towards the end of the measurement window, the FEL gain could reduce $F$ in a manner that is consistent with the measurement.

Still there are a number of uncertainties and sources for error in our procedure. For example, identifying the start of the time window is complicated by the fact that only the lower limit of the fundamental mode intensity in saturation is available from the published Chen-Madey data. Furthermore, the simulated intensity of the fundamental mode may differ somewhat from that measured due to uncertainties in the oscillator parameters, and we have found that errors in power by a factor of two would change the starting point of the observation window by ±3 cavity round-trips.

For these reasons we compared both the Fano factor $F$ and auto-correlation function $G(\tau)$ derived from measurements to those predicted by our simulations assuming several different starting pass numbers and two different models of the dead time. We summarize this comparison in Table 2, where we find that there is a range of parameters and models for which our simulations are consistent with the data.

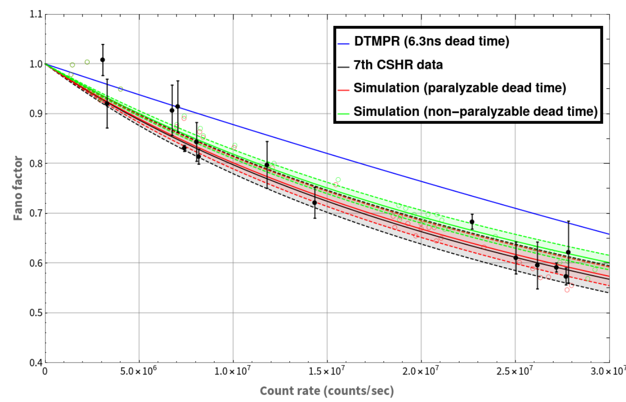


Figure 4: The simulated Fano factor for the found observation window starting at the 58 cavity round-trip. The shaded areas are the 3-$\sigma$ bands, and the error bar represents one standard deviation.

## A PROPOSED IMPROVED EXPERIMENT

The main difference between Chen-Madey analysis and our study is in the degree of the photon clustering within the observation window. In an improved experiment, the degree of photon clustering can be monitored by recording PMT traces over many ensembles. Furthermore, since the photon statistics will depend on the quantum efficiency significantly only if the Fano factor is not close to the unity, photon count at different efficiencies can be performed. With an FEL operating in the visible light regime, the photon statistics at the fundamental mode can also be measured.

## CONCLUSION

According to our simulation of the Fano factor of Chen-Madey experiment, the reduced Fano factor observed in the experiment could also be explained with the standard theory if one combines the detector dead time effect with photon clustering arising from FEL gain. Considering the significance of the claim of sub-Poissonian FEL light made by Chen and Madey, an improved re-measurement may be useful.

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