An Investigation of possible Non-Standard Photon Statistics in a Free-Electron Laser I: Experiment

J.-W. Park

University of Hawaii at Manoa, Honolulu, HI, USA

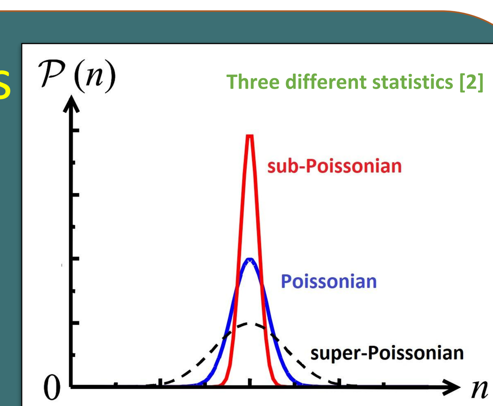
K.-J. Kim, R. R. Lindberg

Argonne National Laboratory, Lemont, IL, USA

FEL19

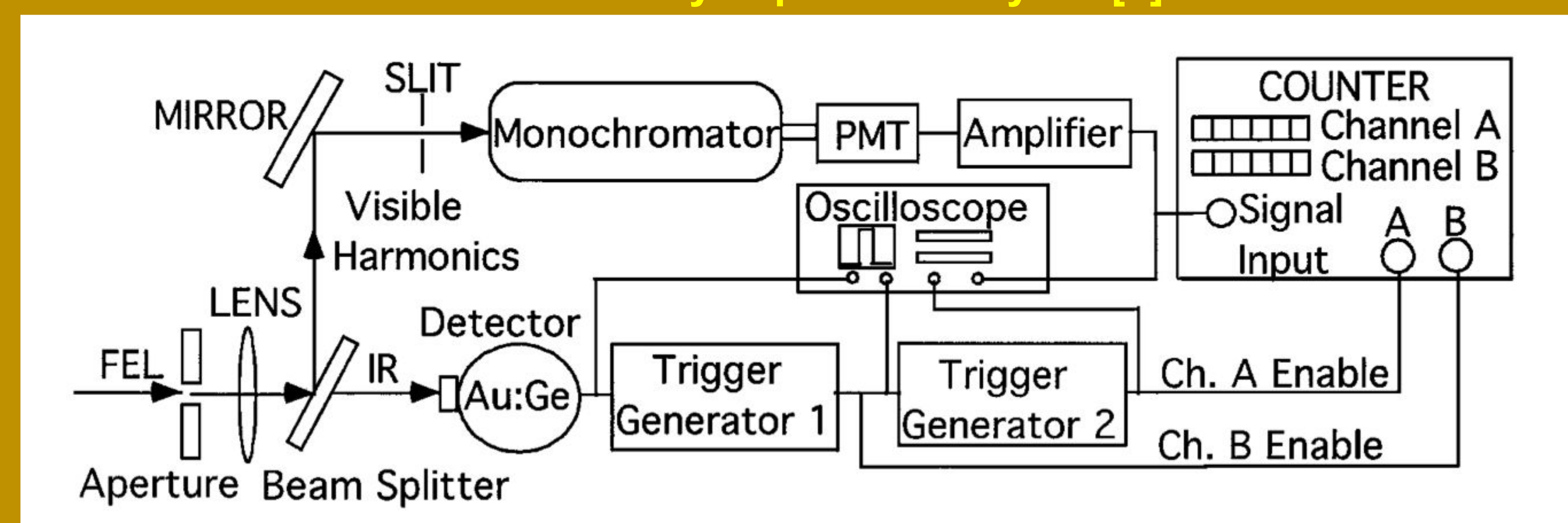
It was reported that the photon statistics of the seventh coherent spontaneous harmonic radiation of the MARK III FEL was sub-Poissonian [1], which concludes that Fano factor F (the ratio of photon number variance to the average photon number) is less than unity. Whether FEL light exhibits such non-standard behavior is an important issue; if it does, our understanding of the FEL needs to be radically modified. 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.

Fano factor of photon statistics



- Fano factor $F \equiv \frac{\langle(\delta n)^2\rangle}{\langle n\rangle} = \frac{\langle n^2\rangle - \langle n\rangle^2}{\langle n\rangle}$
- F>1: Super-Poissonian, e.g. chaotic light
- F=1: Poissonian (coherent light), e.g. light emitted by classical current
- F<1: Sub-Poissonian

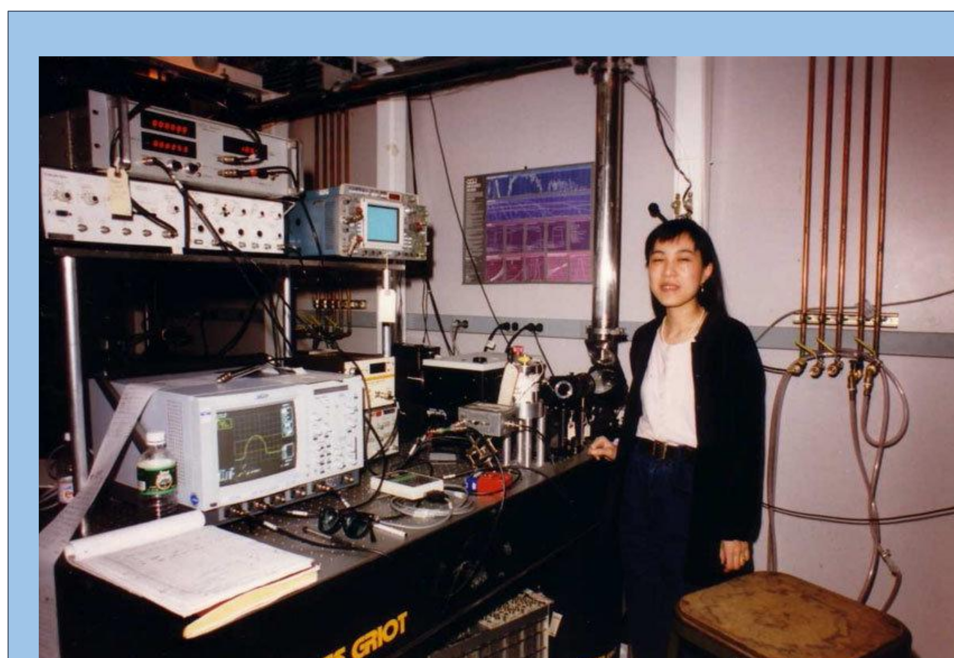
Chen-Madey experiment layout [1]



- Photons emitted by electron macropulse ensembles are counted during the 80 ns observation window (linear regime)
- 7th harmonic mode with high quantum efficiency (12%) is counted (low quantum efficiency results in a measurement of Fano factor of unity despite the actual statistics)
- Count rate is adjusted by the slit size (on average ≲3 photons within the observation window)

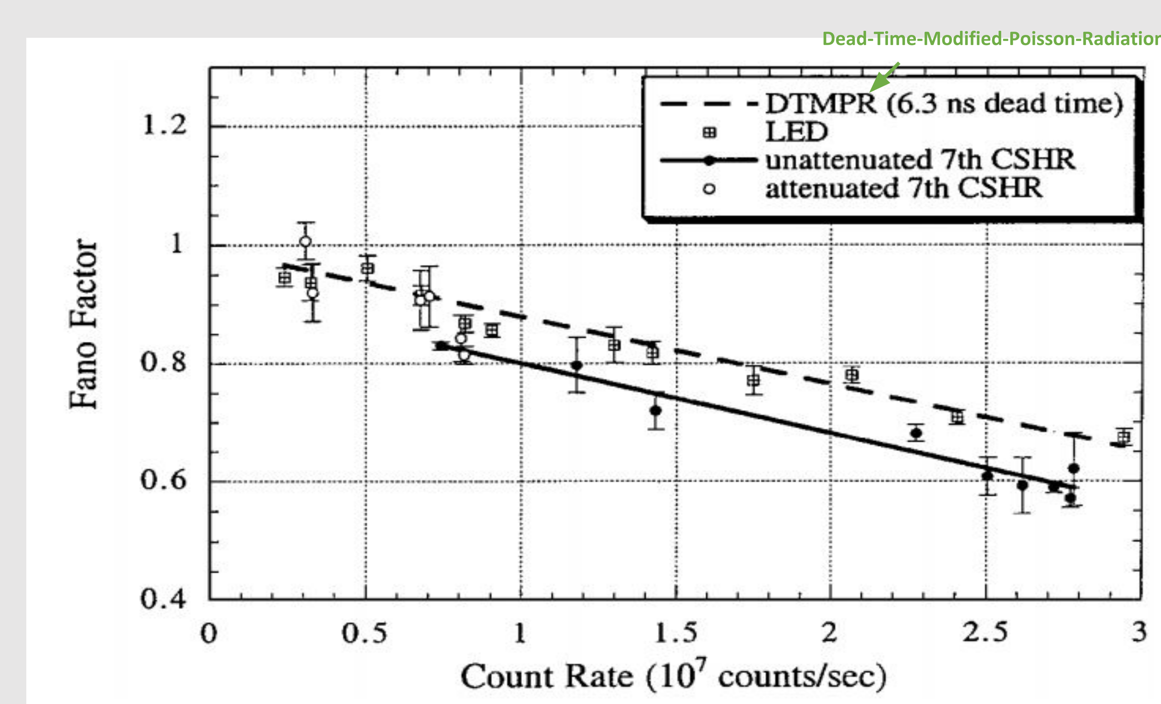
MARKIII FEL specification

Parameters	Value	Unit
K (undulator parameter)	1.13	
λ_u (undulator period)	2.3	cm
λ_1 (fundamental mode wavelength)	2.68	μm
Macropulse length	2	μs
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

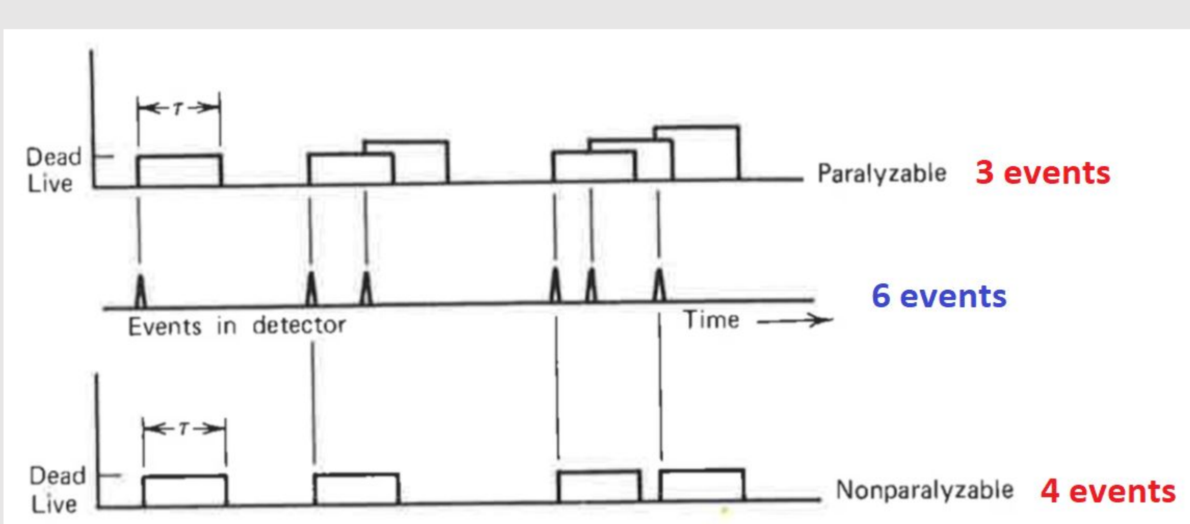


Teng Chen with MARK III FEL [3]

Observed Fano factor reduction [1]



Detector dead time and reduced photon number [4]

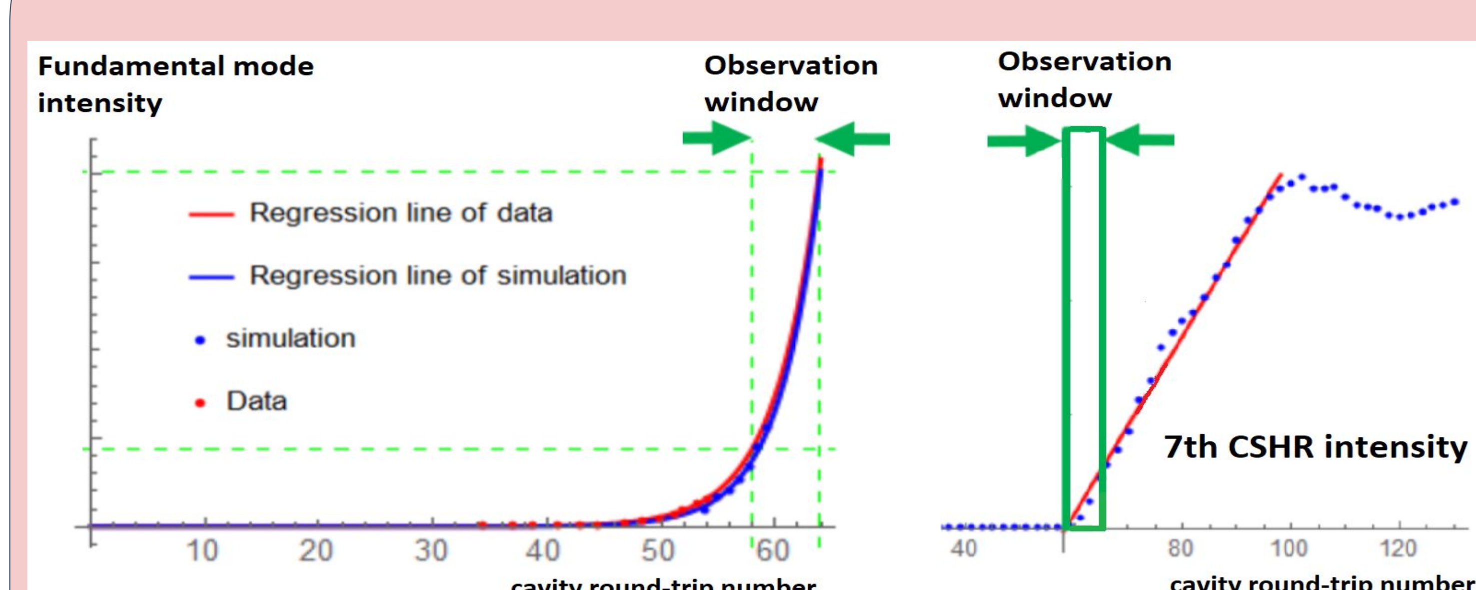


Observed Fano factor can be reduced [5]

How to simulate measurement

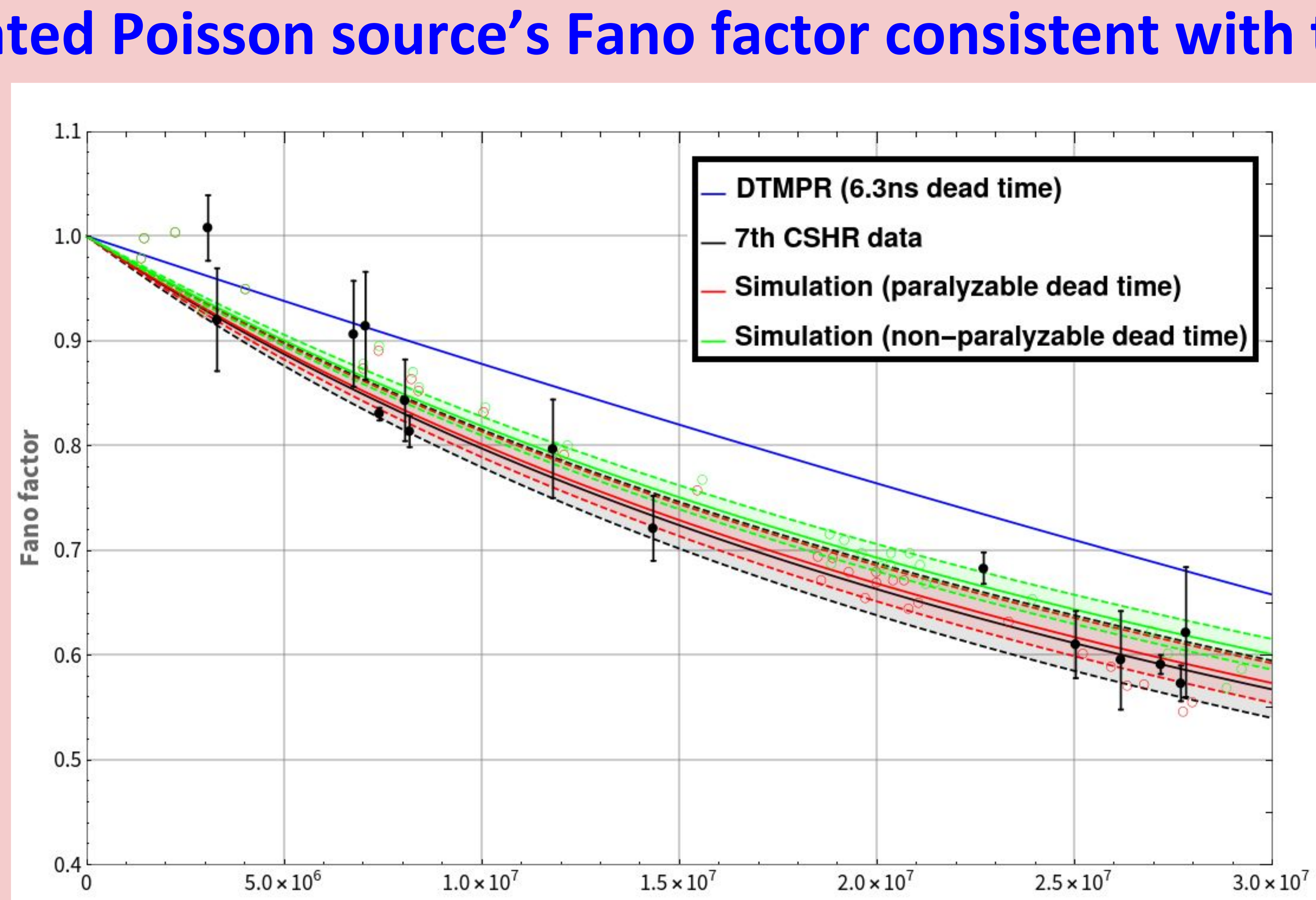
1. GINGER determines the FEL power in the fundamental and seventh harmonic
2. Determine the starting time (pass number) of the 80 ns time window by using the experimentally measured ratio of the power in the fundamental at the start to that in saturation.
3. Determine the seventh harmonic power during the 80 ns window determined in step 2 to set the emission probability, and simulate the measurement including dead time.

80ns observation window found by GINGER simulation



- Simulated observation window starts at the 58th cavity round-trip
- 7th harmonic mode is clustered within the observation window
- The clustering can suppress measured Fano factor beyond that predicted by dead time alone

Simulated Poisson source's Fano factor consistent with the data



Simulated measurement for other nearby observation windows

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	×		×		×		×		△		○		○		○		○	

NP: non-paralyzable daed time, P: paralyzable dead time. ○: consistent, △ : approximately consistent, ×: inconsistent
Auto-correlation: PMT voltage's auto-correlation function

A proposed improved measurement

- Record PMT voltages over many ensembles to trace the photon clustering
- Photon count at different multiple quantum efficiencies
- Photon count of the fundamental mode using a FEL operating in the visible light regime

Conclusion

- 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
- An improved re-measurement may be useful

Acknowledgement

Work supported by U.S. DOE, Office of Science, Office of BES, under Award No. DE-SC0018428

References

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