# SASE FEL Saturation Characterization at the ATF

*X.J. Wang*

National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY

After successful completion of the High Gain Harmonic Generation (HGHG) free electron laser (FEL) experiment [1,2] at the Accelerator Test Facility (ATF), R&D toward future light sources at the NSLS achieved another milestone on March 17, 2001 when the visible-infrared self-amplified spontaneous emission amplifier (VISA) experiment at the ATF achieved saturation. The VISA Self Amplified Spontaneous Emission (SASE) FEL is part of the Linac Coherent Light Source (LCLS) X-ray FEL R&D effort to develop technologies for the proposed X-ray FEL and study the physics of SASE FEL's. The VISA experiment was designed and operated by a BNL/LLNL/SLAC/UCLA collaboration.

The VISA experiment employed a 4-meter long undulator [3] (fig.1) with built-in strong focusing. The undulator has a period of 1.8 cm, with an undulator parameter *K=1.26*. The VISA undulator has a 6 mm gap, which is the same as the proposed LCLS X-ray FEL undulator. The high-brightness electron beam

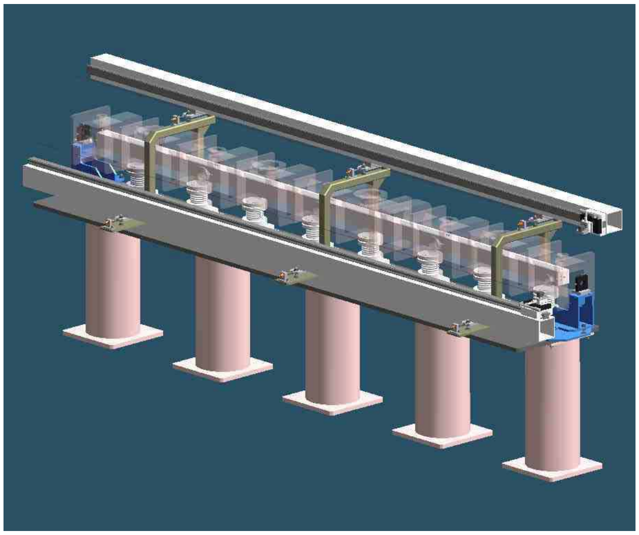

***Figure 1.*** *VISA Undulator.*

coupled with the strong focusing of the undulator results in a 20% reduction in the FEL gain length compared to a conventional undulator, but it imposes some stringent performance requirements on the experiment. The alignment accuracy of the VISA undulator is comparable to that of the LCLS, which is about 50 μm over the 4 meter undulator length. Another unique feature of the VISA undulator is the eight diagnostic ports uniformly distributed along the undulator, which makes it possible to characterize both electron beam and SASE radiation as a function of the undulator length.

One of the key reasons for conducting the VISA experiment at the ATF is the high brightness electron beam produced by the ATF accelerator system [4]. The electron beam is generated by a 1.6 cell photocathode RF gun, and accelerated to 71 MeV by a six-meter long linac. The electron beam was delivered to the VISA experiment by a double bend achromatic transport line and matched into the VISA undulator by a quadrupole magnet triplet.

One of the major challenges for all single-pass, high-gain FEL's is to maintain the overlap of electron beam with the FEL light over distances long enough to reinforce the coupling between them. For the VISA experiment the undulator itself was aligned using a laser interferometer to realize a mechanical straightness of better than 50 μm over the entire undulator length. Beam based alignment techniques were used to correct any undulator alignment and other errors below that tolerance. Finally the SASE FEL output is used to further minimize the trajectory error, and optimize the electron beam properties.

Figure 2 plots the SASE output as a function of the distance along the undulator. Near the end of the undulator, the SASE growth deviated from the exponential growth, which indicates saturation of the VISA SASE FEL. The measured gain length is about 18.7 cm, and the total gain is more than seven orders of magnitude [5].

The achievement of the saturation in the VISA experiment made it possible to further study several basic properties of SASE FEL's. One of consequences of the high gain of this FEL is the presence of large harmonic content in the later stage of the gain; so called nonlinear harmonic generation. Figure 3 is the simultaneous measurement of the first three harmonics from the VISA undulator. The comparatively large second harmonic observed is due to the relatively low electron beam energy employed in the VISA experiment. For the first time, the basic properties of the nonlinear harmonic generation, i.e., the gain length decreasing linearly with the harmonic number, has been experimentally verified [6].

Another experiment was performed using the VISA undulator to study the electron beam micro-bunching in the SASE FEL. One of the fundamental processes for high gain FEL's (both HGHG and SASE) is the lon-

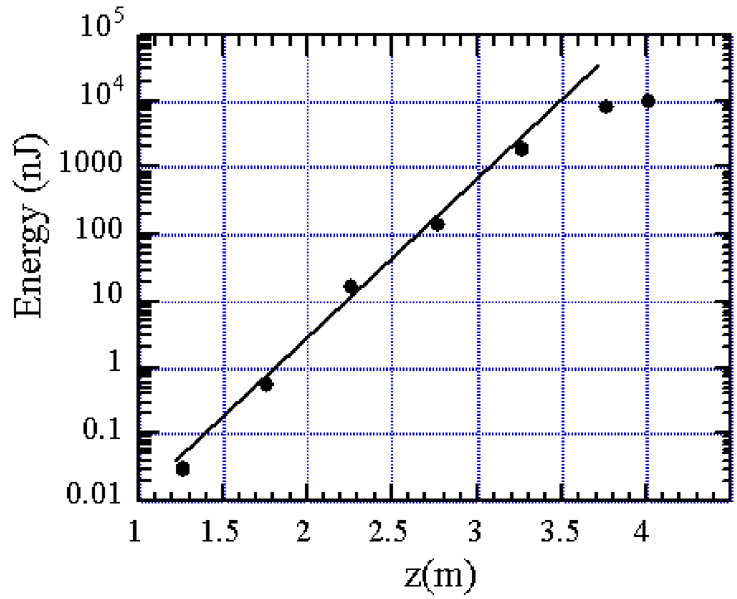


***Figure 2.*** *VISA SASE energy measured as a function of the distance along the undulator.*

gitudinal micro-bunching of the electron beam, which leads to the exponential gain of the output as the beam transits the undulator. A novel coherent transition radiation (CTR) detector was developed to allow the direct study of the correlation between the SASE output and the micro-bunching [7]. Figure 4 is the SASE output and CTR from the electron beam 30 cm from the undulator exit. It shows a direct linear correction between the micro-bunching and SASE until the FEL achieves saturation. This measurement also provides an independent verification of the saturation of the FEL. The micro-bunching for the second harmonic was observed for the first time in the VISA experiment [7].

The VISA experiment successfully delivered a series of important results on the path to high performance FEL's. It achieved the highest gain and shortest gain length yet demonstrated in a SASE FEL. End-to-end simulations were performed that agreed with the results of the VISA experiment. It was also the first time that the electron beam properties required for a future X-ray FEL have been experimentally demonstrated. The fundamental role of electron beam micro-bunching in SASE FEL was directly experimentally verified and nonlinear harmonic generation was systematically characterized at the VISA.

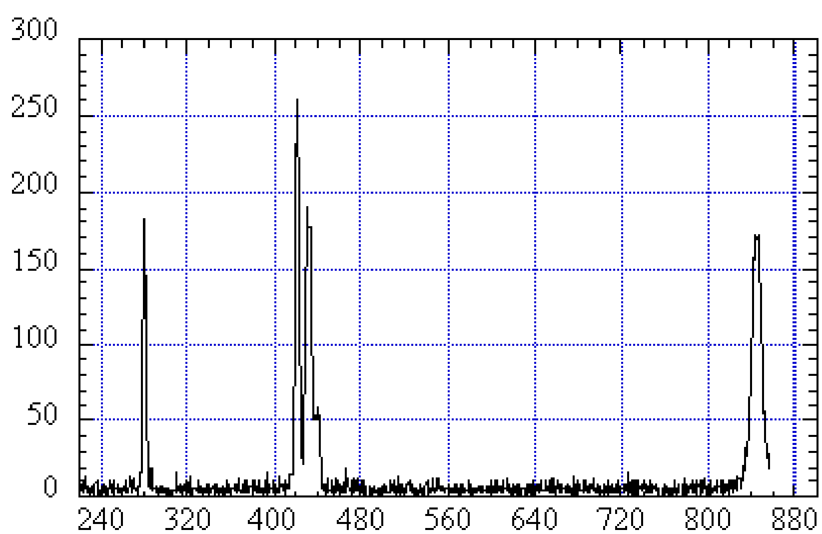


***Figure 3.*** *The single shot spectrum of VISA SASE out; the intensity of the fundamental was attenuated by about two orders of magnitude.*

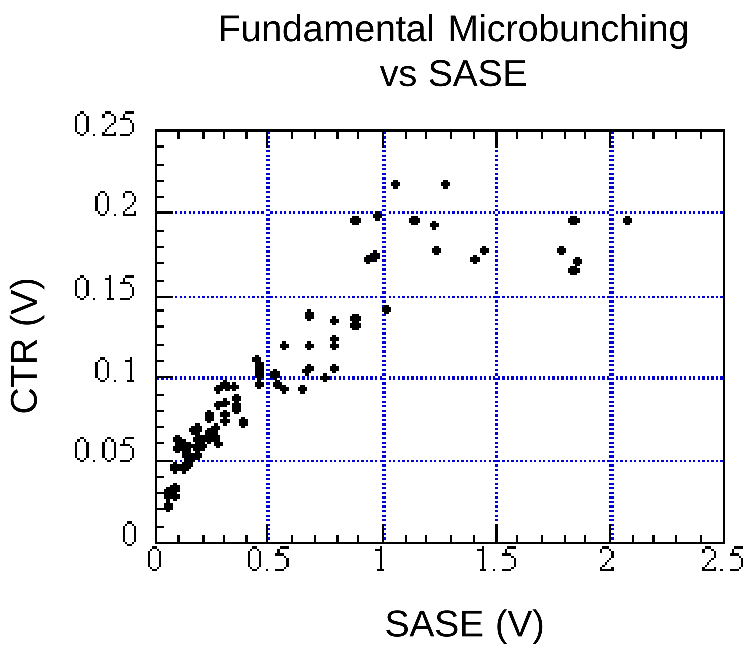


***Figure 4.*** *Micro-bunching (CTR) as a function of the SASE out put; level off of the CTR provides another proof of the saturation.*

## References


[1] L.H. Yu, M. Babzien, I. Ben-Zvi, L.F. DiMauro, A. Doyuran, W. Graves, E. Johnson, S. Krinsky, R. Malone, I. Pogorelsky, J. Skaritka, G. Rakowsky, L. Solomon, X.J. Wang, M. Woodle, V. Yakimenko, S.G. Biedron, J.N. Galayda, E. Gluskin, J. Jagger, V. Sajaev, I. Vasserman, "High-Gain Harmonic-Generation Free-Electron Laser," Science, 289 (2000) 932-936.

[2] Doyuran, M. Babzien, T. Shaftan, L. H. Yu, L. F. DiMauro, I. Ben-Zvi,S. G. Biedron, W. Graves,E. Johnson, S. Krinsky, R. Malone, I. Pogorelsky, J. Skaritka, G. Rakowsky, X. J. Wang, M. Woodle,V. Yakimenko, J. Jagger, V. Sajaev, and I. Vasserman , "Characterization of a High-Gain Harmonic-Generation Free-Electron Laser at Saturation", Phys. Rev. Lett. 86, 5902-5905 (2001).

[3] R. Carr, M. Cornacchia, P. Emma, H.D. Nuhn, B. Poling, R. Ruland, E. Johnson, G. Rakowsky, J. Skaritka, S. Lidia, P. Duffy, M. Libkind, P. Frigola, A. Murokh, C. Pellegrini, J. Rosenzweig, and A. Tremaine, Physical Review Special Topics - accelerators and beams, **4**, 122402 (2001).

[4] X.J. Wang, "Progress and Future Directions in Brightness Electron Sources", Proceeding of 2001 Particle Accelerator Conference, Chicago, IL, June 18-22, 2001.

[5] A. Murokh, R. Agustsson, P. Frigola, C. Pellegrini, S. Reiche, J. Rosenzweig, A. Tremaine, M. Babzien, I. Ben-Zvi, E. Johnson, R. Malone, G. Rakowsky, J. Skaritka, X.J. Wang, V.Yakimenko, K.A. Van Bibber, L. Bertolini, J.M. Hill, G.P. Le Sage, M. Libkind, A. Toor, R. Carr, M. Cornacchia, L. Klaisner, H.-D. Nuhn and R. Ruland, "Properties of a Self-Amplified Spontaneous Emission Free-Electron Laser in Linear Regime and Saturation", submitted to Phys. Rev. Lett, 2001.

[6] Tremaine, X.J. Wang, A. Murokh, C. Pellegrini, M. Babzien, I. Ben-Zvi, M. Cornacchia, H.-D. Nuhn, R. Malone, S. Reiche, J. Rosenzweig and V. Yakimenko, "Experimental Characterization of Nonlinear Harmonic Radiation From a Visible SASE FEL at Saturation", submitted to Phys. Rev. Lett., BNL Report 68545, 2001.

[7] Tremaine, X.J. Wang, A. Murokh, C. Pellegrini, M. Babzien, I. Ben-Zvi, M. Cornacchia, H.-D. Nuhn, R. Malone, S. Reiche, J. Rosenzweig and V. Yakimenko, "Fundamental and Harmonic Microbunching in a High-Gain, Self-amplified, Spontaneous Emission Free-Electron Laser ",submitted to Phys. Rev. Lett., 2002.