REMEMBERING SAMUEL KRINSKY

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Abstract

This year, we lost our colleague Samuel Krinsky. Sam has made many important contributions to very broad field of accelerator physics. In remembrance of his life and achievements, we will review his contributions to the field of free electron lasers. In particular, we will concentrate on his contributions to the foundation of the theory of high gain FELs, and his managerial and experimental contributions to pioneer work on x-ray FEL development.

Figure 1: Sam Krinsky January 14, 1945 - April 26, 2014.

SAM'S CONTRIBUTIONS

Sam has made contributions in accelerator physics covering very broad areas. Among many of these contributions to accelerator physics, we focus on the following:

• NSLS X-ray ring (1978) design and commissioning
• First short-period in-vacuum undulator at NSLS (1987)
• First global orbit feedback system at NSLS
• Design NSLS-II storage ring (2014)
• Important contributions to studies of impedances and collective effects including the theory on coherent synchrotron radiation and micro-bunching in electron beams.
• Founded Source Development Laboratory at BNL

We will not be able to cover such broad areas of research works in these proceedings. Instead, we shall concentrate on his contributions to free electron laser physics.

Among many other contributions made by Sam, we would like to highlight his most important seminal contributions to the FEL community. We shall categrize these contributions in two aspects: theoretical basis for high gain FEL, and leading experimental and managerial roles.

Among Sam's many contributions to the theoretical basis of high gain FEL physics:

• Universal gain scaling function [1]
• 3-D SASE start-up noise [2]
• Effect of wiggler errors [3]
• Average spacing of peaks in SASE spectrum [4]

We also recognize among many of his leading experimental and managerial roles:

With his managerial skill and foresight, Sam contributed decisively to the formation of FEL team. This led to the creation and successful execution of FEL projects at Brookhaven National Laboratory during his tenure as deputy chairman of the NSLS department, paving the way toward many accomplishments with important impacts on the worldwide short wavelength FEL development. Here we highlight some of the most significant of these:

• Facilitated the 1990 Sag Harbor "Prospects for a 1 Å Free Electron Laser" Workshop with R. Palmer.
• 1997-1999 ATF HGHG Experiment at 5 μm:
Sam was instrumental in getting the NSLS to provide resources to the BNL Accelerator Test Facility to complete R&D on the photo-injector and to carry out the HGHG proof-of-principle experiment in the infrared.
• Leading role in the construction of the DUVFEL at the SDL for 2000 -2003 HGHG Experiment at 266 nm.

SCALING FUNCTION OF GAIN

In 1990, collaborating with L. H.Yu and R. Gluckstern, Sam derived an FEL integral differential equation describing evolution of the electric field strength E in an undulator, taking into account of diffraction, optical guiding, energy spread, emittance, detuning, focusing and betatron oscillation [1]:

$$(\Delta_\perp^2 + \Omega)E(\vec{r}) = \frac{i}{2}(2\rho\gamma_0)^3 \int \frac{d\gamma}{\gamma^2} h'(\gamma) \int d^2p \int_{-\infty}^{0} ds e^{-i\alpha s} u(p^2 + \kappa^2 r^2) E[\vec{r}\cos(\kappa s) + \frac{\vec{p}}{\kappa}\sin(\kappa s)]. \quad (1)$$

This equation has many eigen-solutions, each representing an eigen-mode of the optical guiding, giving the gain of the

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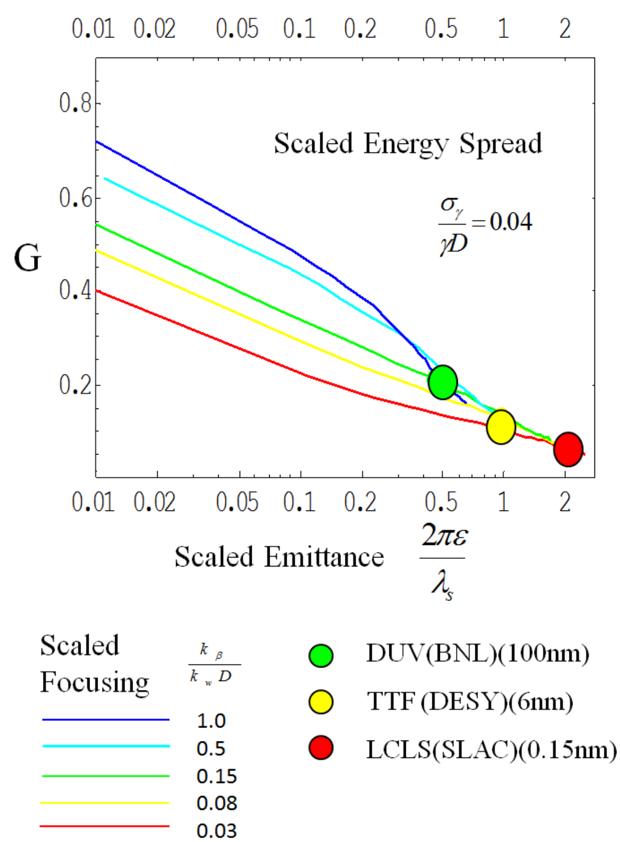

Figure 2: Scaling gain function showing the parameters of 3 FEL facilities.

electric field strength E. The mode with the highest growth rate dominates and gives scaling gain as function of the scaled emittance, energy spread, beta function, and detuning. The scaled gain can be represented by two different forms. The first form is:

$$\frac{1}{2k_w L_G^{3D} \rho} = \frac{\mathrm{Im}\Omega}{\rho} \equiv G(\tilde{a}, \frac{\sigma}{\rho}, k_s \varepsilon, \frac{\omega - \omega_s}{\omega_s \rho}), \quad (2)$$

In the second form, it is:

$$\frac{1}{2k_w L_G^{3D} D} = \frac{\mathrm{Im}\Omega}{D} \equiv F(k_s \epsilon, \frac{\sigma}{D}, \frac{k_\beta}{k_w D}, \frac{\omega - \omega_s}{\omega_s D}), \quad (3)$$

The first form scaled with the FEL parameter ρ, is suitable for comparison with 1-D theory, showing the deviation from the 1-D theory for a perfect beam due to the diffraction, finite emittance, detuning, and energy spread.

The second form scaled with the scaling parameter D, which is determined only by the current and the energy of the electron beam, hence is independent from current density or beam size. As we can see in the following, this second form is suitable for scaling down from long wavelength to short wavelength FEL.

Sam, R. Gluckstern and I calculated the Scaling function using variational method and checked with codes from Los Alamos and Lawrence-Livermore. We found excellent agreements with the codes, with errors within few percents which is determined mosly by the simulation itself. Later when we compared the scaled parameters for several FEL projects, we found we can put them on one plot. Even though the wavelengths of these FELs change by several orders of magnitudes , the scaled parameters are not very far from each other on the plot. In Fig. 2, we plot the scaled parameters for DUVFEL of BNL, the TTF FEL of DESY, and for LCLS.

The scaling function provides fast calculation of gain length,and as a benchmark vs. codes, it serves as the basis for high gain FEL calculations

Two years later, in 1992, Ming Xie fit our scaling function formula to polynomials, which is widely used in world FEL community, and known as "Ming Xie's formula".

1990 SAG HARBOR "PROSPECTS FOR A 1 Å FREE ELECTRON LASER" WORKSHOP

When we worked out the scaling function for FEL gain, we were equipped with a powerful tool to scan large parameter space to find the optimized FEL gain for short wavelength. Sam then initiated a discussion with R. Palmer (BNL's Dir. Office). The goal was very clear: we would like to inform our lab's management office of the potential of x-ray FEL, and influence the future development direction. We worked out a table on a blackboard, which listed the parameters of several X-ray FELs (see Fig. 3). R. Palmer recognized the importance of this new trend immediately, and decided to organize a workshop on x-ray FEL. The workshop is the 1990 Sag Harbor "Prospects for a 1 Å Free Electron Laser" Workshop. The table we generated on the blackboard has been published in the proceedings of this workshop, and is copied here as Fig. 3:

We can see that the LCLS parameters (proposed after 1992) is quite close to the last column of this table, apparently off by a factor 2. Notice that the last column of the table is for a 1 angstrom x-ray FEL while LCLS design goal is 1.5 angstrom. Also notice that in 1990 our assessment was that the normalized emittance of 2 mm-mrad was achievable by RF photo-cathode gun in the foreseeable future, hence we used the normalized emittance of 2 mm-mrad instead of the 1 mm-mrad which later appeared in LCLS design report. Hence the difference between the LCLS and our last column of the table in 1990 is within even less than a factor of 2.

We copied the front page and the contents of the 1990 Sag Harbor "Prospects for a 1 Å Free Electron Laser" Workshop in Fig. 4.

During the workshop, C. Pellegrini first presented a general talk about SASE and x-ray FELs. Then I presented a paper about the scaling relations and the parameters for 1 angstrom FEL, with the table of Fig. 3 included in the paper, which is just the table we established on the blackboard during the discussion with R. Palmer, as we mentioned before. Then a paper authored by a group including H. Winick and C. Pellegrini was presented about a 40 angstrom FEL based

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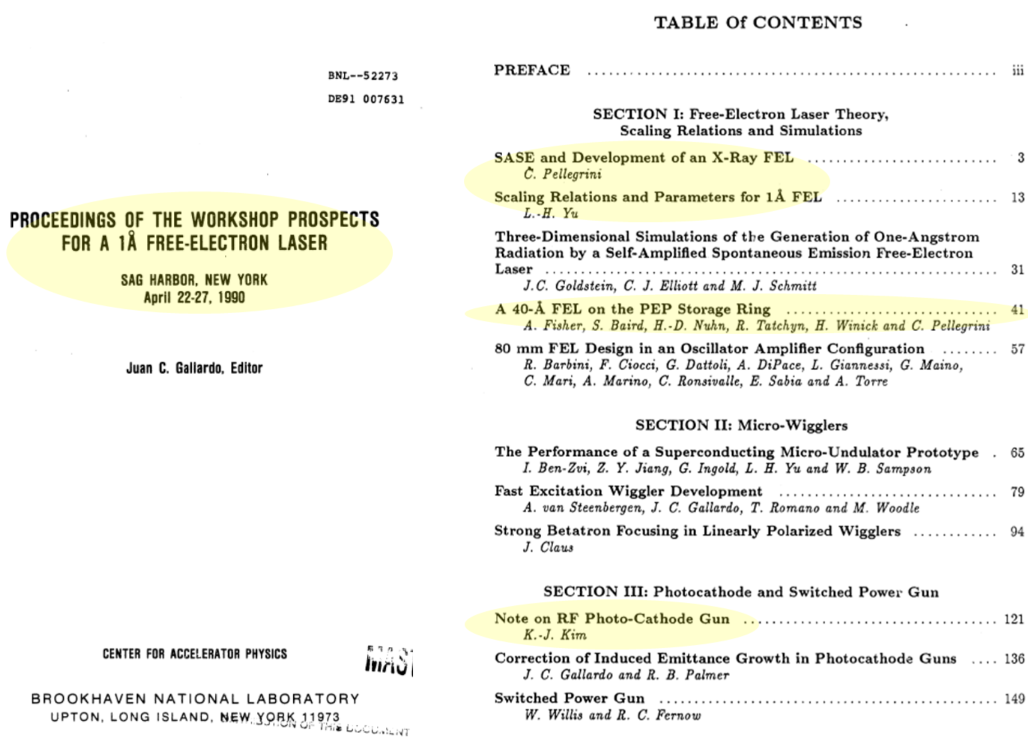
E(GeV)	0.25	5	1.67	50	28
K	1	1	1	5.2	3.7
B_w	1.07	1.07	10.7	0.8	1
λ(Angstrom)	400	1	1	1	1
λ_w(cm)	1	1	0.1	7	4
ϵ_n(mm-mrad)	4	0.2	0.07	2	2
$\sigma(x10^{-3})$	1	1	1	1	1
I(Amp)	100	2000	670	10360	10360
power gain length (m)	1.73	1.73	0.17	12.1	9.9
λ_β(m)	6.28	6.28	0.628	44	26
natural λ_β(m)	6.9	140	4.8	1860	830

Figure 3: Table of parameters for several FELs, copied from Sag Harbor workshop proceedings.



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PROCEEDINGS OF THE WORKSHOP PROSPECTS FOR A 1Å FREE-ELECTRON LASER

SAG HARBOR, NEW YORK
April 22-27, 1990

Juan C. Gallardo, Editor

CENTER FOR ACCELERATOR PHYSICS

BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

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Figure 4: Contents of Sag Harbor 1 Å Free Electron Laser Workshop

on PEP storage ring. K.J.Kim also gave a talk about RF photo-cathode gun in the workshop.

This workshop clearly has an important impact on the future development of x-ray FELs. We quote from E-mail of H. Winick to A. Sessler on May 9, 2013:

'The 1990 Sag Harbor workshop on "Prospects for a 1 A Free-Electron Laser" was a very important event. I point this out in my talks and recently received several copies of the proceedings from Gallardo, which I distribute to those interested.'

Two years later, in 1992, H. Winick organized the workshop "1992 Workshop on Fourth Generation Light Sources, SLAC". This workshop also had important impact on the later development of LCLS. Two papers generated during this workshop are directly related to LCLS: one is a paper by W. Barletta, A. Sessler, L.H. Yu, "Using the SLAC Two Mile Accelerator for Powering An FEL", SLAC-PUB-15126, 1992, the other is a paper by C. Pellegrini "A 4 to 0.1 nm FEL based on the SLAC Linac", Proceedings Workshop on Fourth Generation Light Sources, 1992. We represent the connection of these two workshops to the advent of LCLS as in Fig. 5. A photo taken during the 1990 Sag Harbor workshop on "Prospects for a 1 Å Free-Electron Laser" is given in Fig. 6.

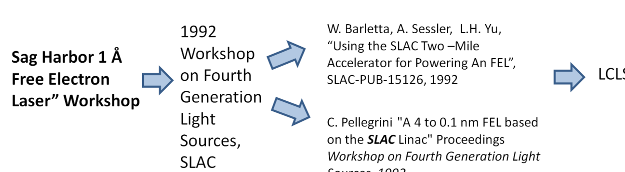

Figure 5: Connection of two workshops with LCLS.

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Figure 6: Photo taken during the 1990 Sag Harbor workshop on "Prospects for a 1 Å Free-Electron Laser".

FEL EXPERIMENTS AT ATF AND SDL

With his managerial skill and foresight, Sam contributed decisively to the formation of FEL team, the creation and successful execution of FEL projects at Brookhaven National Laboratory during his tenure as deputy chairman of the NSLS department, which led to many important accomplishments with important impact on the worldwide short wavelength FEL development.

In particular, Sam's support of the first HGHG experiment to generate 5 micron FEL output from 10 μm seed from a 10 μm CO_2 laser at ATF was critically important for its success. The work generated a publication in the journal "Science" in 2000 [5]. With Sam's support we were able to develop BNL RF-photo-cathode gun at the ATF and achieved emittance at 1 mm-mrad at 0.7 nC, a significant achievement at that time. In Fig. 7 we show the photo taken during the acquisition of "Cornell Wiggler A" for 1997-1999 ATF HGHG Experiment at 5 μm, where Sam was standing in the front, with full energy and spirit.

Figure 7: Photo taken during the acquisition of "Cornell Wiggler A" for 1997-1999 ATF HGHG Experiment at 5 μm.

Following this experiment, Sam started the organization of Source Development Laboratory (SDL). Sam's leading role in the construction of SDL was again crucially important for the success of the DUVFEL. The success of HGHG at 266 nm with more than 130 micro joules with seed at 800 nm shows high stability and Fourier transform limited spectrum. In Fig. 8 we show the HGHG spectrum with a comparison of the SASE spectrum. The experiment demonstrated the basic principle of the HGHG.

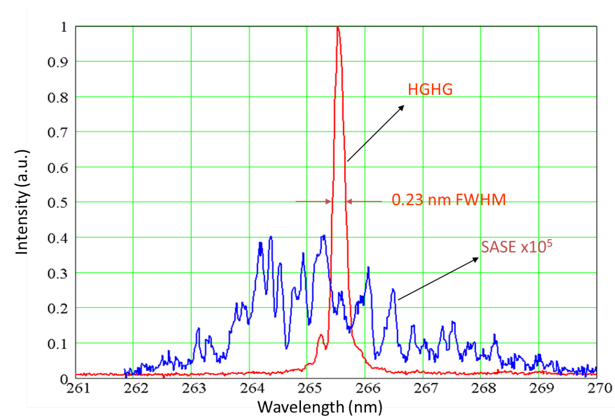

Figure 8: HGHG spectrum with a comparison of the SASE spectrum

Both these two experiments have important impact on the later development of coherent FEL based on the HGHG principle.

EFFECT OF WIGGLER ERRORS

Another of Sam's contribution to high gain FEL theory is the theory on the effect of wiggler errors [3]. It seems to be a rather complicated problem at first. However, we were able to reduce this problem to the solution of a rather simple equation:

$$y''' - i(\delta' y)'' = i(2\rho k_\omega)^3 y, \tag{4}$$

where δ is the phase error due to wiggler errors. The analysis of this equation shows that the condition for the damaging effect of the wiggler error to be small is the phase error accumulated in one gain length should be much smaller than 1 radian.

Another interesting conclusion from the solution of this equation using Born approximation is that the criterion on the peak to peak amplitude error is largely relaxed, the criterion for negligible gain reduction is

$$\frac{2\pi}{9\sqrt{3}} \frac{K_0^4}{(1+K_0^2/2)^2} \frac{(\Delta B/B)^2_{\rm rms}}{\rho} \ll 1. \tag{5}$$

This result means that $(\Delta B/B)^2_{\rm rms}$ should be smaller than ρ, the FEL paramter. Before the derivation of the this equation and its solution, the intuition seems to be that we should require $(\Delta B/B)_{\rm rms} \ll \rho$, which is a much more stringent condition. For example, for LCLS, $\rho \sim 10^{-4}$. Thus the

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first impression is we require $(\Delta B/B)_{\rm rms} \ll 10^{-4}$. However this work about wiggler error points to the requirement of $(\Delta B/B)^2_{\rm rms} \ll 10^{-4}$, i.e.,$(\Delta B/B)_{\rm rms} \ll 10^{-2}$, a much more relaxed condition.

As a result of this, the work emphasizes the importance of phase error in one gain length dominated by error of mean value in one gain length and the trajectory deviation from the axis, and prescribes the alignment tolerance as:

$$P = P_0 e^{-\left(\frac{x_{\rm rms}}{x_{\rm tol}}\right)^4}, \quad (6)$$

where P_0 is the FEL power without wiggler error, while P is the power with wiggler error in the linear exponential regime.

When the distance between the correction station $L_s \ll$ the gain length L_G, we have the tolerance of trajectory within a gain length as:

$$x_{\rm tol} = \left(\frac{L_s}{L_G}\right)^{\frac{3}{4}} \times 0.266 \sqrt{\lambda_s L_G} \left(\frac{L_G}{z}\right)^{\frac{1}{4}}. \quad (7)$$

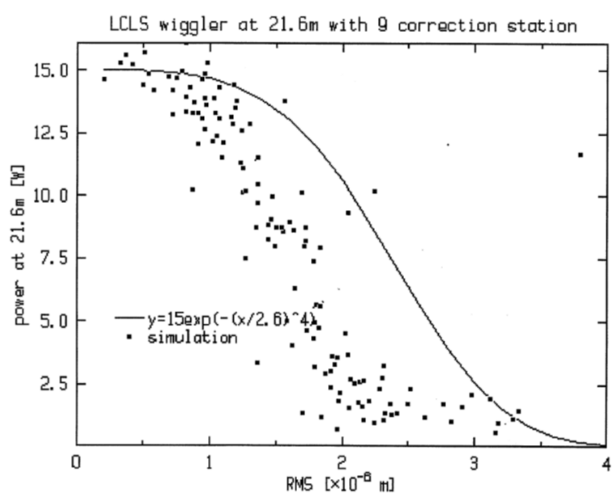

Figure 9: Power versus RMS trajectory errors obtained by the above formula and simulation.

For LCLS, we find $x_{\rm tol} = 2.6\ \mu m$. In Fig. 9, we compare the power as function of RMS trajectory error obtained from the above formula and simulation result. The result shows the simulation result indicated is a little more stringent than our result.

AVERAGE SPACING BETWEEN PEAKS IN SASE SPECTRUM [4]

Another example of Sam's work is very useful during experiment. This is the work on the statistical properties of SASE radiation. Even though the analysis of the SASE spectrum has been carried out previously, Sam's analysis provides a very simple way to obtain the length of the electron bunch. Once we see the SASE spectrum, we can use the average spacing between the peaks in the spectrum to deduce the pulse length. We choose a section of the spectrum, and count the number of peaks in the section to calculate the average spacing between the peaks to be about 0.35nm during one of the SASE experiment at SDL as shown in Fig. 10. The formula then gives:

$$T_b = \frac{\lambda^2}{0.64\ c\Delta\lambda} = \frac{(266nm)^2}{0.64 \times 3 \times 10^8 m/s \times 0.35nm} \approx 1ps. \quad (8)$$

This result is in good agreement we obtained using zero phasing method during the experiment. This is typical of Sam's theoretical works: it is tightly connected to experiments.

Due to the limited space and time, some of Sam's important works were not described here. For example, the work on 3-D SASE start up noise [2] described in details about how the noise is amplified and how it creates many competing modes, how and under what condition these modes are finally dominated by a single fastest growing mode, how the transverse coherence is developed during this process, and how these modes are related to the the spontaneous radiation of the first two gain lengths of the undulator, how much of this radiation is coupled into the different transverse modes, etc. Hence the theory is directly related to the saturation length, the coherence properties of the output radiation, etc.

Finally, I would like to thank Faith Krinsky for providing the video of Sam's conversation.

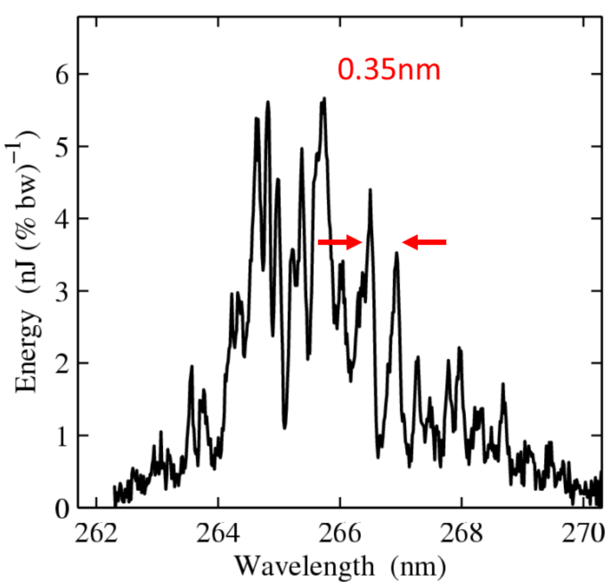

Figure 10: Intensity spiking in the frequency domain (arbitrary units). In the single-shot spectrum, the width of the peaks is inversely proportional to the electron bunch duration T_b.

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