FEL SPECTRAL MEASUREMENTS AT LCLS*

J. Welch†, F-J. Decker, Y. Ding, P. Emma, A. Fisher, J. Frisch, Z. Huang, R. Iverson, H. Loos, M. Messerschmidt, H-D. Nuhn, D. Ratner, J. Turner, J. Wu, SLAC NAL, Menlo Park, Ca. USA

Abstract

We report measurements made at LCLS of average and single shot spectra of x-ray FEL radiation, including correlations with chirp and bunch current. And, for normal- and over-compressed beams, we show the relationship between the electron energy distributions before the undulator and FEL spectra. We find the bandwidth of normally compressed beams can approach the theoretical minimum SASE bandwidth, though only for relative weak beams. Over-compressed beams can have large bandwidth with fwhm of 2% or more and pulse energy comparable to normally compressed beams. In this case the bandwidth is dominated by electron energy spread and the FEL radiation is probably chirped.

INTRODUCTION

An experimental study of FEL spectra at LCLS is warranted because of the importance of spectral width in experiments, and because it increases the understanding of accelerator physics phenomena that go into making the beam. Arguably, the performance parameter that most distinguishes an FEL from other light sources is the brightness — the density of photons in six-dimensional phase space — with spectral width being one of the factors in the denominator. For the experimenters a beam with narrow spectral width implies more photons are at a known and desired energy, so useful data can be collected with less background and at a greater rate. For accelerator physicists FEL spectra provide an entire dimension of information needed to understand and improve present performance and to invent new modes of operations such as chirped FEL, and new machines of superior performance. [1]

UNDERLYING PHYSICS

On the most basic level the SASE process itself, coupled with the tuning of the undulator, determines the FEL spectrum. As a function of distance along the undulator the spectral bandwidth is expected to decrease as the beam approaches saturation, reach a minimum of about $\rho\omega_1$ rms at saturation, and then increase the post-saturation. Here ρ is the dimensionless Pierce Parameter and ω_1 is the fundamental frequency of the FEL radiation. [2]

Wakefields and the slope of accelerating RF fields produce a correlated energy along the length of the electron bunch known as chirp. Different slices of the bunch can therefore lase at different wavelengths, and the result is manifested in the measured spectra. Correlations between slice gain, which depend on the local current and emittance, and slice energy may combine so that the dominate contributions to the measured spectra arise from the highest gain portion of the bunch.

Incoherent energy spread will randomly increase the spread in resonant frequencies of different slices and in principle can contribute to an increase in the measured spectral width. However if the amount of incoherent energy spread is large enough to affect the spectral width it also is large enough to reduce the FEL gain, so it tends not to be significant in the measured spectra. The primary sources of incoherent energy spread are spontaneous radiation and laser heater excitation [3, 4, 5]. For the 13.6 GeV beam the calculated rms relative energy spread due to spontaneous radiation at the end of the undulator is 1.3×10^{-4} which is substantial below the SASE bandwidth which is of order 1×10^{-3} . Normally the laser heater is tuned to around 20 keV rms energy spread, which when multiplied by the typical compression factor of 100 corresponds to relative energy spread of 1.5×10^{-4} at 13.6 GeV.

MEASUREMENTS

We present two sets of measurements made at LCLS in September 2010. In the first set the beam energy was nominally 13.6 GeV but scanned slightly so as to sweep the FEL spectrum across the pass-band of a monochromator [6] and be detected on a photodiode. The result was average spectra of several hundred shots. The shot-to-shot energy jitter, which is sometimes of the same order as the bandwidth, was taken out by measuring the electron beam centroid energy on each shot, using beam position monitors a dispersive region, and shifting FEL data accordingly. The second set of measurements used a beam energy of 5.28 GeV and the SXR spectrometer to measure the spectrum on each shot. In the 5.28 GeV data set electron energy distributions were measured upstream of the undulator using a wire scanner in a dispersive region. For an overview see Figure 1. Beam parameters applying to all spectra in are given in Table 1.

Monochromator Measurements at 13.6 GeV

Measured FEL spectra from the 13.6 GeV set are shown in the two plots of Figure 2 for selected peak currents in the normal compression case (left plot), where the original front of the bunch is still in the front of the bunch after compression, and for the over-compressed case (right plot) in which a higher degree of chirp is applied and the front and back of the bunch change places. The FEL beam was atten-

* Work supported in part by the DOE Contract DE-AC02-76SF00515.
† welch@slac.stanford.edu

ISBN 978-3-95450-117-5

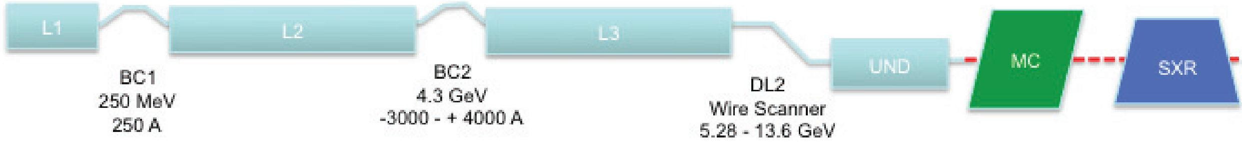

Figure 1: Schematic showing the linac section L2 where chirp is applied, the dispersion section DL2 where electron energy measurements were made; and the monochromator and spectrometer, where the spectral measurements were made.

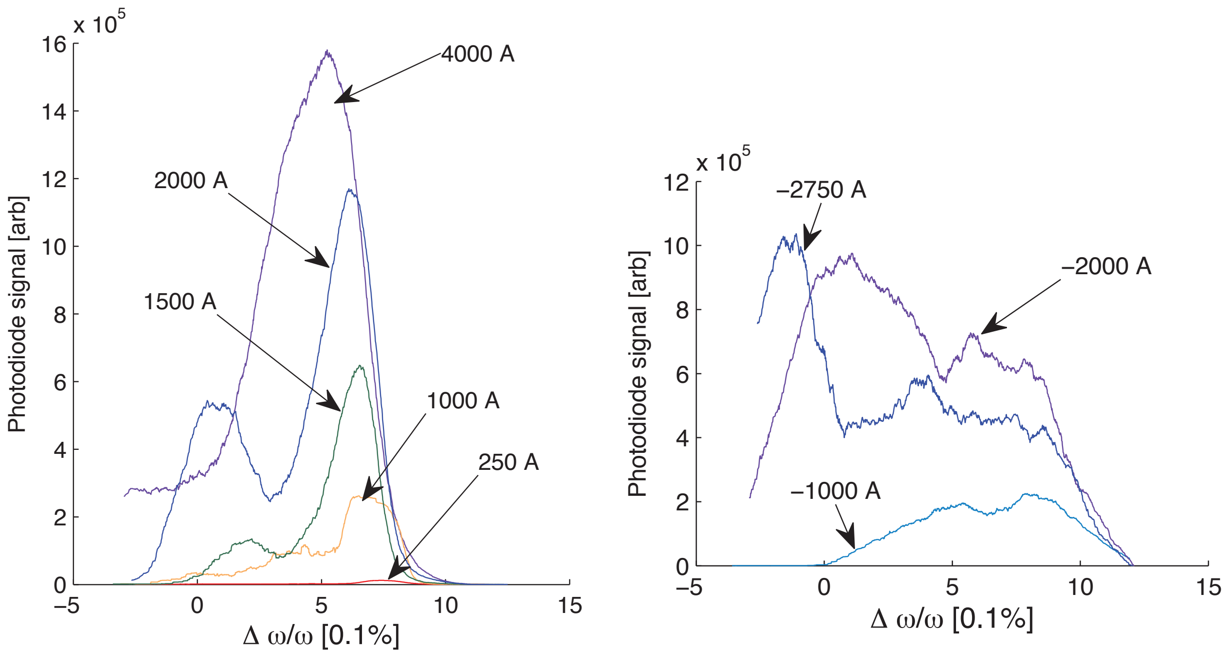

Figure 2: Measured FEL spectral dependence on peak current (and chirp) for normal compression (left plot) and for over-compression (right plot) at constant charge and beam energy. By convention negative current implies overcompression.

Table 1: Machine parameters that were held constant during while the compression in BC2 was varied and spectra were taken

BC2 Energy	4.3	GeV
Bunch Charge	250	pC
BC1 Peak Current	250	A
BC2 R56	- 24.7	mm
Heater Energy rms	20	keV

uated by beryllium foils, passed through a monochromator and detected on a photodiode. Attenuation and photodiode gain were held constant during the measurements so the relative peak heights and integrated areas of each spectrum are indicative of the FEL gain dependence on current. The relative position of each spectrum are meaningful. All spectra where obtain with the same bunch charge and undulator tuning. Spectra are plotted as a function of a relative frequency detuning from the theoretical peak for first harmonic. Spectral widths are quoted in units of [0.1%] relative to the fundamental frequency. For clarity the data have been smoothed using a moving window average but not so much so that the fwhm increases significant.

One can see in Figure 2 that peak FEL spectral brightness occurs around 2000-4000 A despite the fact that the fwhm is clearly not at a minimum. Furthermore, with increasing current the peaks shift toward lower photon energy and most of the additional power is added on the low energy side of the peak. The total pulse energy is proportional to the integral over the spectrum. For this data set the over-compressed beam had the highest maximum pulse energy.

At 250 A normal compression there is barely any FEL lasing. As the applied chirp and compression are increased both the amplitude and width of the spectra increase, and the peak of the spectrum shift to lower photon energy. A 'shoulder' on the low photon energy side of the peak that shows up at 1000 A turns into 'double-humps' at 1500-2000 A and back into a shoulder at 4000 A. As the chirp increases further the beam passes through the point of maximum compression where no FEL signal is observed. The first observed over-compression spectra is at -2750 A. It too has a shoulder feature but this time it is on the high photon energy side of the peak and it has a much wider spectral width. Further increases of applied chirp cause of length-

ISBN 978-3-95450-117-5

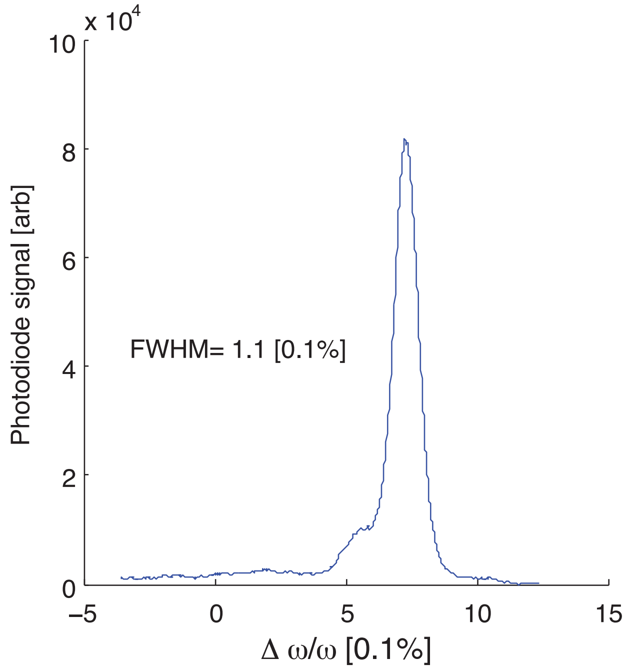

Figure 3: Narrowest bandwidth is observed for long low current bunches with low FEL output power. In this plot the peak current was only 500 A.

ening of the over-compressed bunch, a decrease in the peak current, and a decrease spectral width.

For peak currents of 1000 A or less, the Pierce parameter is estimated to be $\rho \approx 0.4$ [0.1%] or less, and the fwhm measures about 1-2 [0.1%] (see Figure 3 for one example) corresponding to an rms of roughly 0.5-1 [0.1%] consistent with SASE theory [2]. At higher currents and more substantial output power the measured bandwidth is larger than the minimum predicted at saturation from theory.

Spectrometer Measurements at 5.28 GeV

The second set of spectral data was taken using the SXR spectrometer [7] to measure single-shot spectra at the fundamental photon energy of 1220 eV. Electron energy distributions for normally and over-compressed 1500 A beams were also measured using a wirescanner upstream of the undulator .

Figure 4 shows the measured fwhm as a function of peak current for both the normal- and over-compression.[1] The fwhm is a minimum at the lowest current (longest bunch length) under normal compression and steadily grows with increasing current beyond 4000 A. The Pierce parameter for these currents ranges approximately from $0.4 - 1.4 \times 10^{-3}$ corresponding to a SASE fwhm bandwidth of 1.4 - 4.9 [0.1%] assuming a rectangular bunch — close to the measurements. For over-compression the fwhm is much

[1] Three data points were removed as they had relative large 'double humps' and the second hump was captured in the FWHM.

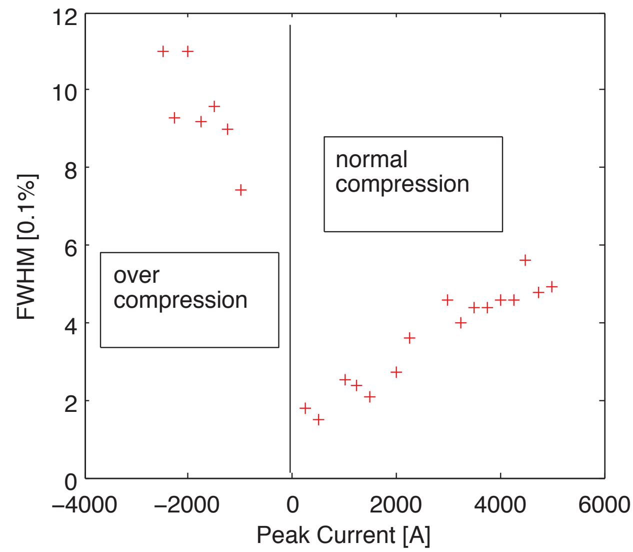

Figure 4: FEL bandwidth dependence for fixed charge and varying current, for both normal compression and over-compression measured on the SXR spectrometer.

larger and grows rapidly as the bunch nears maximum compression.

The measured fwhm are much greater for over-compression than normal compression for the same nominal bunch length. A possible explanation is that in over-compression the applied chirp from accelerating RF adds to the energy chirp due to wakefields (because the head and tail interchange during compression), while it subtracts from the wakefield chirp for normal compression. But it should be noted when a beam is over-compressed it must pass through a point of maximum compression where the high currents could generate coherent synchrotron radiation and change the energy distribution.

A comparision of the electron energy distribution before it enters the undulator and the resulting FEL spectra is shown in Figure 5. The energy distribution is an average measured over many pulses and the width includes a contribution from electron energy jitter, so the true single shot energy width is less than the measured 2.9 [0.1%] fwhm. More interesting is the same comparison for the over-compression case at the same bunch length, -1500 A, shown in Figure 6. The shape and width of both the energy distribution and spectra are consistent with the notion that the FEL spectra is dominated by electron energy spread. The peak in the electron energy at relatively low energy deviation has a corresponding peak in the FEL spectral pak at low photon energy, and the FEL spectrum width is just about twice the energy distribution width, as would be expected if compressional changes in the electron energy distribution did not much affect the FEL gain for each slice.

ISBN 978-3-95450-117-5

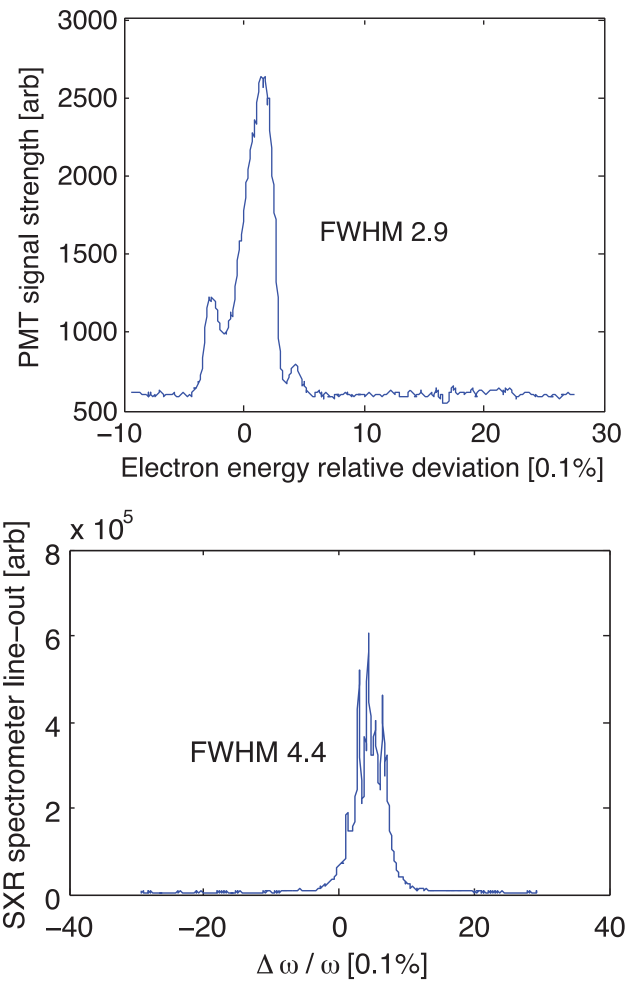

Figure 5: The upper plot show 10-shot average energy distribution measured at the end of the linac about 200 m before the undulator. The lower plot shows a single show spectra taken at SXR. Beam current was 1500 A.

.

CONCLUSIONS

Measurements show the shape of the FEL spectra can be complex, with double humps and substantial shoulders that depend on the bunch length. For longer bunch length under normal compression, the spectrum was found to be the narrowest and bandwidth was in agreement with basic SASE theory. For shorter bunch length, where the FEL output power is higher, the measured bandwidths were larger than theory, but the beam had the highest spectral density. For over-compression the electron energy spread dominates the photon bandwidth and for the shortest bunch length FEL beam probably had a significant FEL chirp of 1% or more.

ACKNOWLEDGEMENTS

The authors would particularly like to acknowledge the talented MCC staff who helped by run the machine during the data taking.

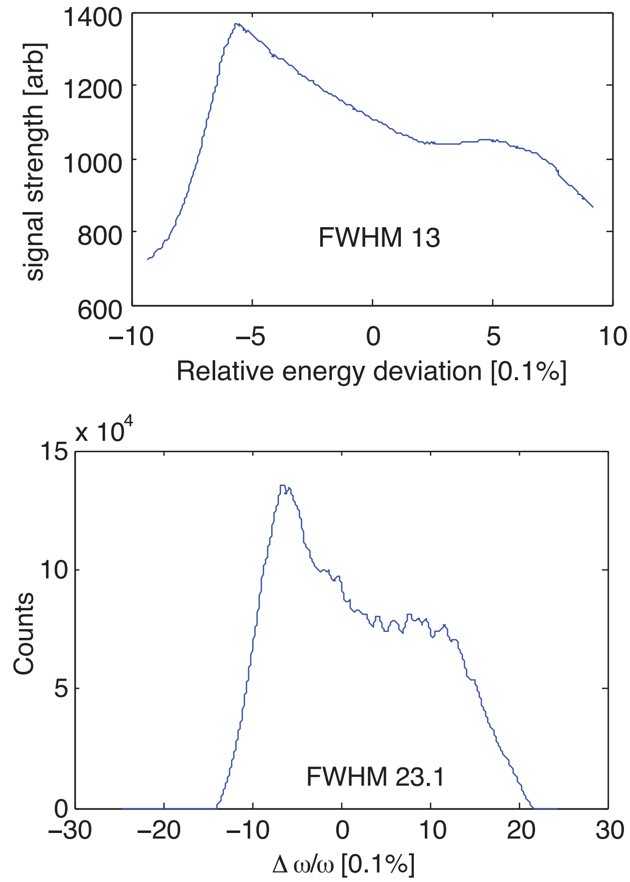

Figure 6: Average electron energy distribution (upper plot) in the dog-leg section of LCLS before the undulator for over-compressed beam at −1500 A. The resulting spectra measured on the SXR spectrometer is shown in the lower plot.

.

REFERENCES

[1] S. Krinsky and Z. Huang, “Frequency chirped self-amplified spontaneous-emission free-electron lasers”, PRSTAB 6, 050702 (2003)

[2] Z. Huang and K-J. Kim, “Review of x-ray free-electron laser theory”. PRSTAB 10, 034801 (2007).

[3] Z. Huang, et. al., “Suppression of microbunching instability in the linac coherent light source”, PRSTAB 7, 074401 (2004).

[4] P. Emma, et.al., “First Results of the LCLS Laser-Heater System”, Proc. of PAC09, WE5RFP041, 2009.

[5] P. Emma, et. al., “First lasing and operation of an ngstrom-wavelength free-electron laser”, Nature Photonics 4, 641-647 (2010)

[6] J. Welch, et. al., “Undulator K-Parameter Measurement at LCLS”, Proc. of FEL09, THOA05, (2009)

[7] P. Heimann et al., “Linac Coherent Light Source Soft X-ray Materials Science Optical Design and Monochromator Commissioning”, Review Scientific Instruments, to be published.

ISBN 978-3-95450-117-5