# FEL OVERCOMPRESSION IN THE LCLS*

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*Abstract*

Overcompression of the Linac Coherent Light Source (LCLS) x-ray Free Electron Laser (FEL) at the SLAC National Accelerator Laboratory is studied. The studies and some operational implications are summarized here.

## INTRODUCTION

The needs of XFEL users lead to exploring the LCLS parameter space. Some experiments benefit from a broad spectrum x-ray beam. Inducing projected energy spread across the electron bunch leads to a transformation into broader photon spectrum. Overcompression, is where in the second bunch compressor the head of the bunch slips back behind the tail, adding to the wake induced energy spread in subsequent L3 linac. This induces a relatively large energy deviation along the bunch typically leading to broader spectrum at the cost of reduced x-ray intensity. A method is being developed where performance can be improved by lasing using only the core of the electron beam.

## DIAGNOSTICS

Two very useful pulse-to-pulse diagnostics are relied upon in these studies: a hard x-ray single-shot spectrometer (HXSSS) [1] (Figure 1), and an x-band transverse deflecting RF cavity (XTCAV) [2].

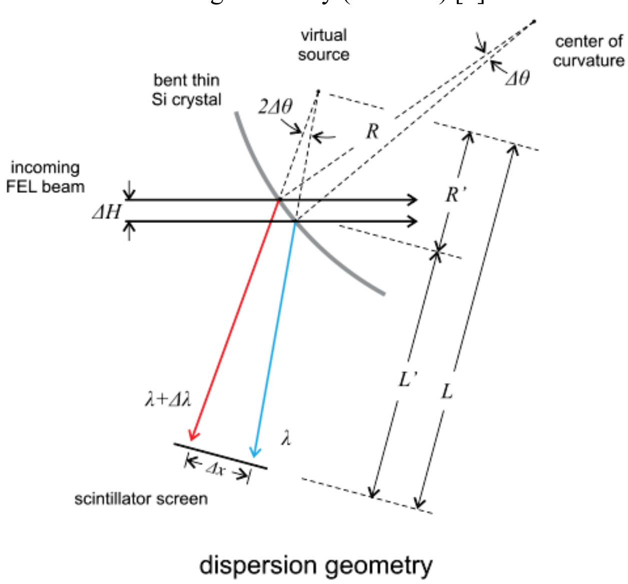


Figure 1: X-ray beam comes in from the left, a small percentage is dispersed by different energies having different Bragg angles from the bent Si crystal. Figure from Ref. [1].

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The cylindrically bent Si(1 1 1) transmissive crystal membrane spectrometer [1] samples different energies across the beam vertical profile, you get amplitude response which is a function of the Gaussian beam profile. To the extent that the beam is larger than the area sampled this makes the response more uniform. In any case, this can be accounted for by nearby beam profile measurement. What you see is the SASE lines in a spectrograph. (Figure 2). The full bandwidth for the data taken was about 120 eV with resolution down to about 1 eV.

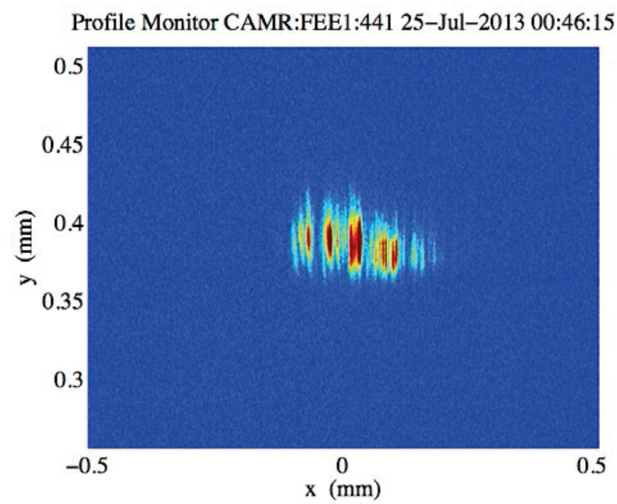


Figure 2: The SASE spikes can be seen dispersed in energy by the spectrometer crystal which in this case is Si(1 1 1). The imaged is rotated, so energy is on the X axis.

### *The XTCAV*

After the electrons exit the undulator, the XTCAV streaks the beam in the horizontal plane, then beam become dispersed in the final bend magnets (Figure 3). The result is an image on a YAG screen which has time for a horizontal axis and energy on the vertical. By taking a non-lasing pulse for reference, images of the electrons during lasing can be used for temporal reconstruction of the x-ray pulse (Figure 3).

## REFERENCE DATA

Typical LCLS machine running is undercompressed (see Figure 4) where the LCLS compression scheme leads to the development of high peak current at the head and tail of the beam that are apparent with the temporal reconstruction of the x-rays.

Empirical tuning of the FEL intensity can lead to beta-match and undulator taper match to either the ends or the

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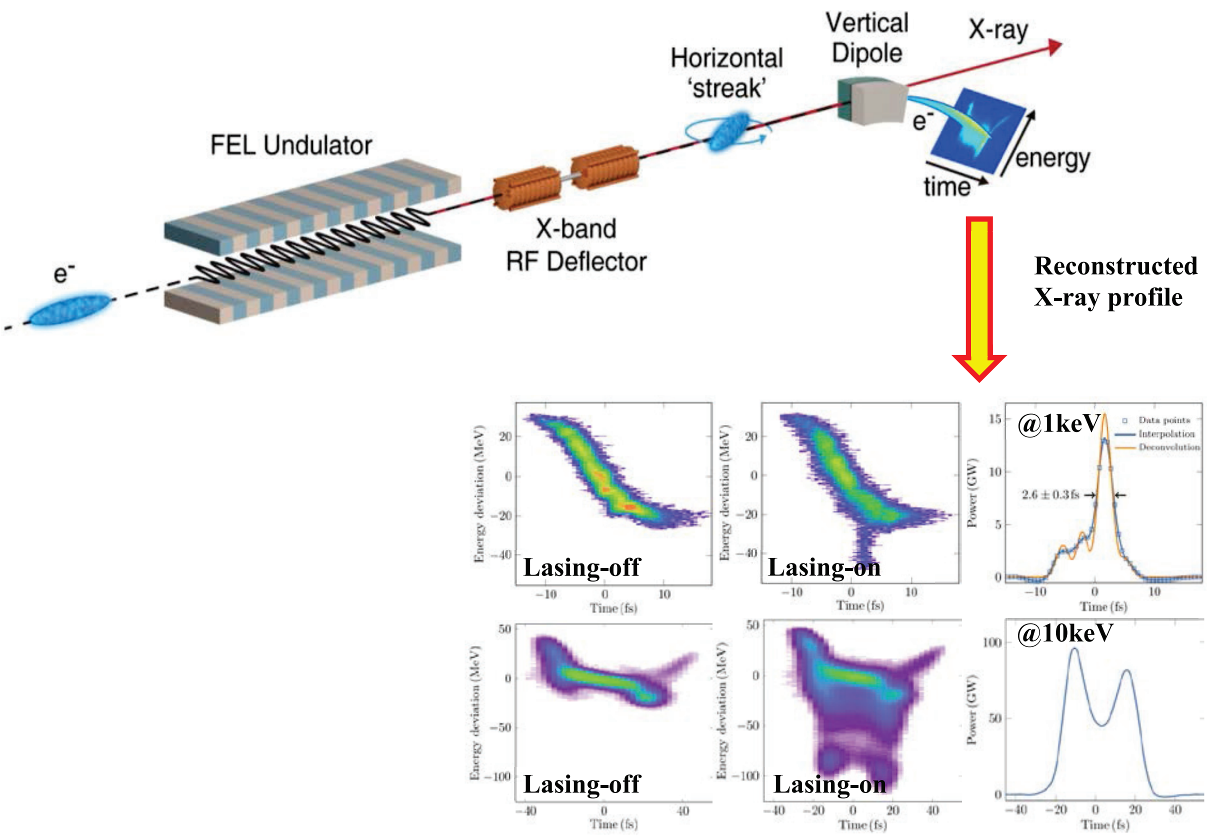


Figure 3: The XTCAV setup. Electrons pass through the undulator, then land on the zero-crossing of the x-band RF creating a horizontal streak. They are then bent and dispersed in the vertical plane. In plots below, reference "lasing off" on the left where 1 keV case is on top and 10 keV case is on bottom. Middle plots are lasing on and right is x-ray temporal reconstruction. Figure from Ref. [2].

center of the beam, or some combination. This can be seen clearly on the XTCAV diagnostic as lasing in the center or the beginning and/or end (see Figure 3, 1 keV "Lasing-on" where lasing is at the end of the pulse).

In Figure 4, see typical good case where the ends and center are lasing, with ends somewhat more than center.

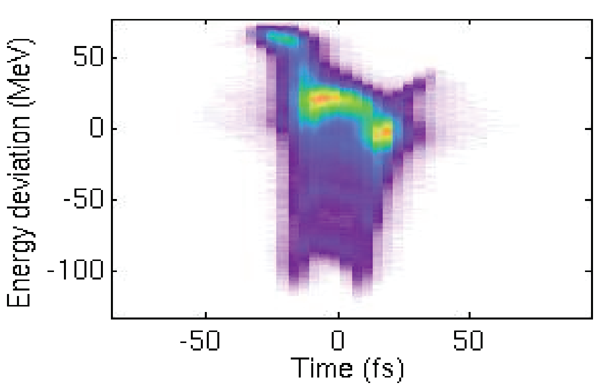


Figure 4: XTCAV data, 8.3 keV, 180 pC, undercompressed (nominal)

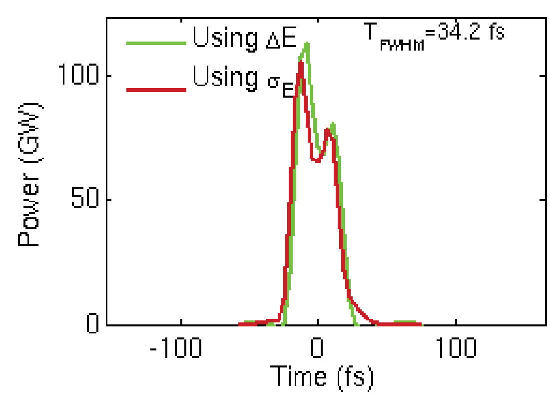


Figure 5: XTCAV data, same conditions as Figure 4.

Figure 5 shows the results of two methods of calculating the x-ray power profile, one using the centroid energy loss of each slice [3] (Equation 1), and a second using the change in the energy spread of each slice (Equation 2).

$$\mathbf{P}_{\mathrm{FEL}}(\mathbf{t}) = [\langle \mathbf{E} \rangle_{\mathbf{FEL\ off}}(\mathbf{t}) - \langle \mathbf{E} \rangle_{\mathbf{FEL\ on}}(\mathbf{t})] \times \mathbf{I}(\mathbf{t}) \quad (1)$$

$$\mathrm{P}_{\mathrm{FEL}}(\mathrm{t}) \propto \left[\sigma^2_{\mathrm{E,FEL\ on}}(\mathrm{t}) - \sigma^2_{\mathrm{E,FEL\ off}}(\mathrm{t})\right] \times \mathrm{I}^{2/3}(\mathrm{t}) \quad (2)$$



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The spectrum for this nominal 8.3 keV x-ray beam (Figure 6) is fitted with a Gaussian and has a FWHM of 20 eV.

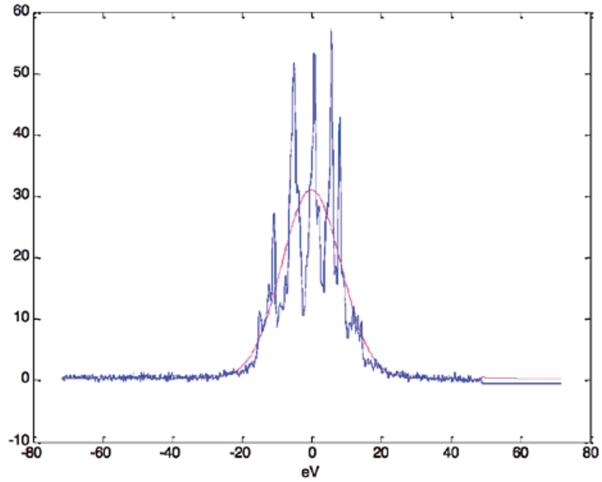


Figure 6: Nominal 8.3 keV undercompressed spectrum, fitted with a Gaussian. FWHM is 20.0 eV for this shot.

## OVERCOMPRESSION 250 PC

Inducing projected energy spread across the electron bunch leads to a transformation into broader photon spectrum. Overcompression, as employed here, where in the second bunch compressor the head and tail switch places, induces a relatively large energy deviation along the bunch. The injector current is raised at this point in the experiment to 250 pC away from the nominal 180 pC. This also contributes to the spectral broadening.

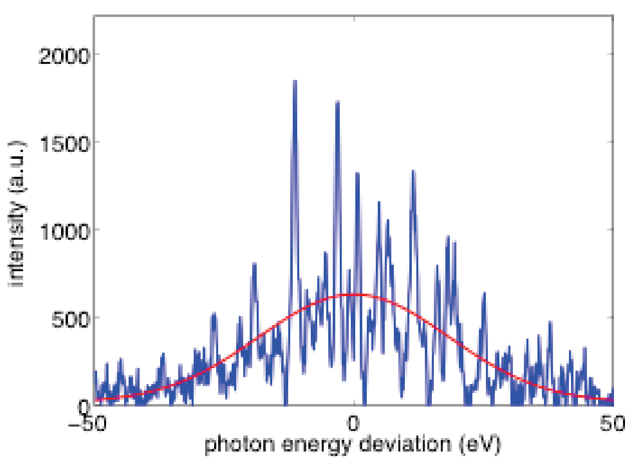


Figure 7: , Fitted FWHM = 44 eV from the spectrometer. 250 pC throughout the LCLS at 8.3 keV nominal energy,

Figure 7 shows the x-ray spectrum is double the nominal with overcompression at 250 pC. This is a single shot, but the average fitted value for about 4000 shots is 43 eV FWHM (not shown).

Lasing top of Figure 8 is clearly in the middle of the beam pulse. Power is ~170 GW.

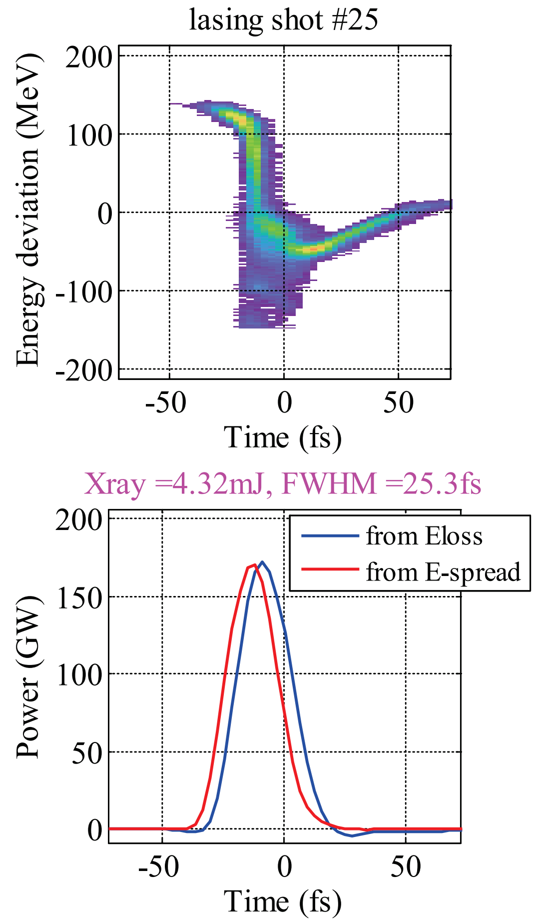


Figure 8: Top is from XTCAV where lasing is clearly only in the middle of the bunch. 4.32 mJ in 25.3 fs is ~170 GW.

## CUTTING 250 TO 170 PC

### *Simulation Cutting to 150 pC Undercompressed*

Simulation in 2011 by Yuantao Ding shows that cutting the head and tail ("horns") of the temporal distribution will allow stronger compression in the second bunch compressor (BC2) due to less CSR effects hence a higher peak current in the core is achievable (see Figure 9). The cut is by collimation in the first bunch compressor (BC1).

In this simulation, 5kA is anticipated in the cut core at 13.6 GeV, 8.3 keV.

### *Experiment Cutting from 250 to 170 pC in BC1*

Figure 10 shows the profile monitor at high dispersion in the middle of BC1 and the actual cut to match the simulation.

### *Experiment Undercompressed Cut Beam*

The XTCAV data shows the peak power attained in simulation could be realized in experiment. Figure 11 left bottom shows 5 kA could indeed be realized. See the upper left "baseline" shot where lasing is suppressed and the linearity of the core, then the upper right where the energy drop of the electrons show lasing across the core. 4mJ in 21fs, is 200GW. The measured spectrum is also



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reduced to about 12 eV FWHM for this horn-cut beam at undercompression. This is to compare the regular undercompressed beam shown in Figure 6.

### *Experiment Overcompressed Cut Beam*

We can also operate the cut beam in an overcompression mode. In this way, a very high peak current over 7 kA has been measured, which helps further improve the FEL peak power. Figure 12 on the right is the spectrum at 40.3 eV FWHM. Figure 12 left 4 blocks are XTCAV data showing 5.36 mJ in 13.8 fs for a peak 350 GW were obtained in experiment. Lasing of the core after linearizing longitudinal phase space by cutting off the head and tail is key here since both the undulator taper match and betatron match can be more uniform across the beam

## CONCLUSION

Excellent pulse to pulse diagnostics such as the HXSSS and XTCAV with guidance by simulation can change your direction of study and broaden FEL capabilities. We achieve a factor of 2 increase in bandwidth as simulated.

Overcompression after cutting "horns" off of the core has great potential, and further studies are planned. Because of the large projected energy spread, dispersion after BC2 (Second Bunch Compressor), any downstream chromaticity, and divergence correction at the last bend in BC2 are issues to pursue.

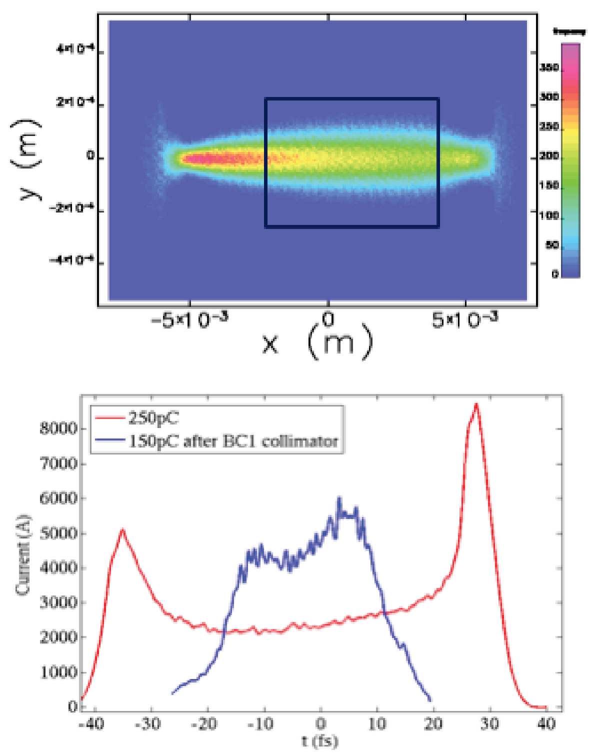


Figure 9: Simulation at BC1 of the cut to achieve the simulated 5 kA (top). This is an asymmetric cut of 6.4 mm offset by +1mm. Result of Elegant runs (bottom) before and after optimizing L2 chirp in each case.

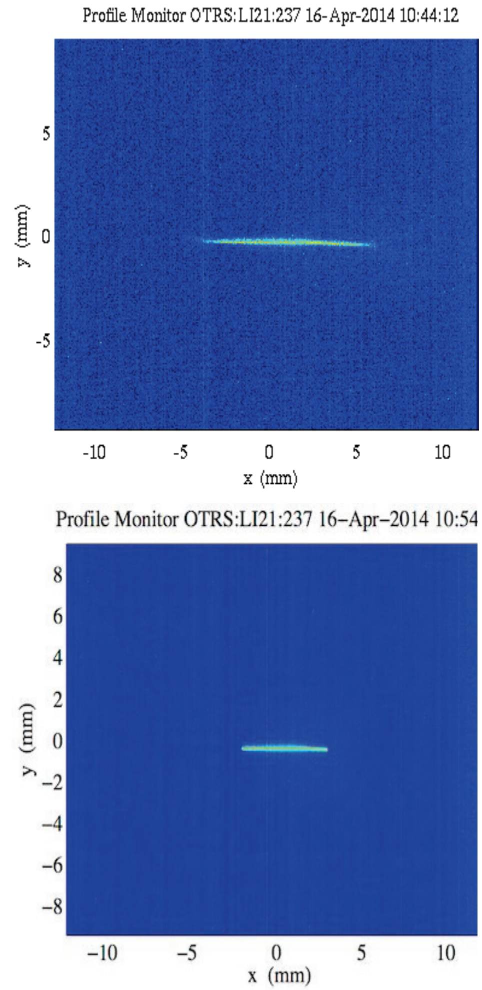


Figure 10: Experimental cut applied in BC1. The profile monitor is in the middle of the chicane just beyond the collimators employed. Top is before, bottom after

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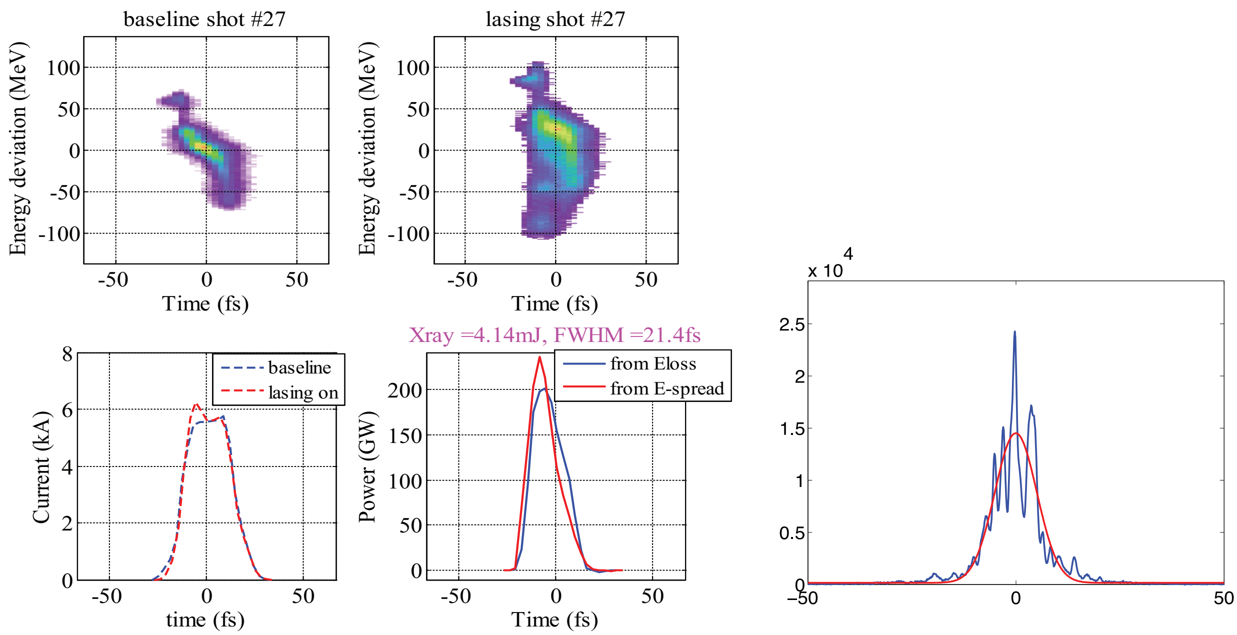


Figure 11: The actual result from XTCAV data, Top left is non-lasing reference, center top is lasing, bottom left is peak current profile and bottom center is peak power. 4mJ in 21fs, 200GW. Spectrum is shown on the right and fitted to be 11.9 eV FWHM.

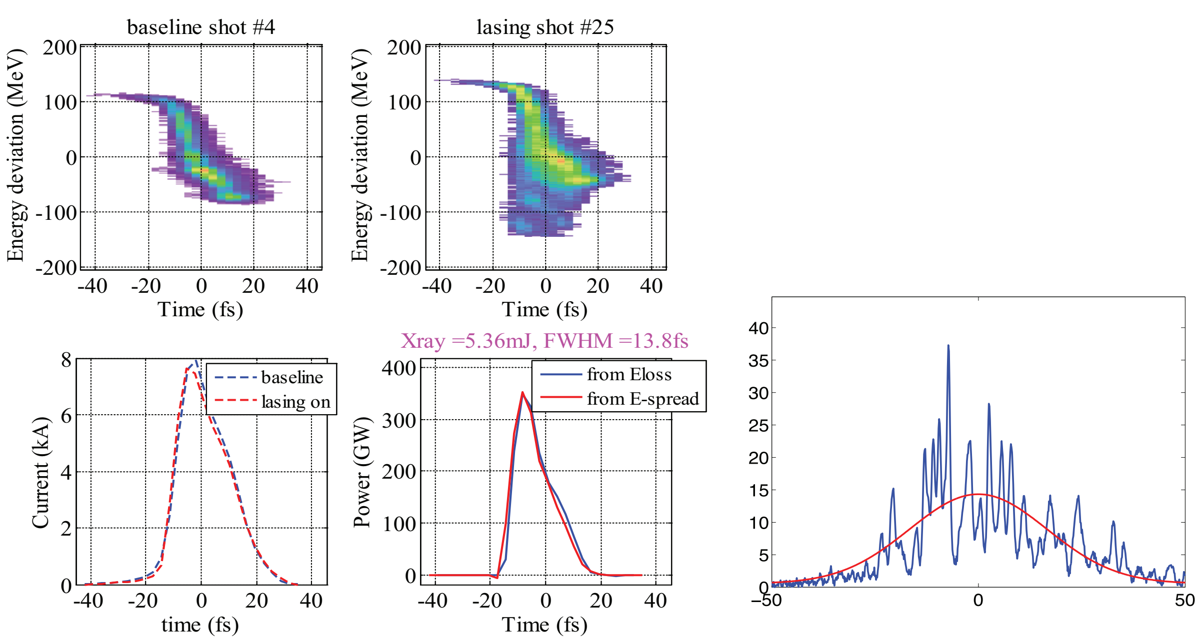


Figure 12: Cut horns (250 pC to 170 pC), overcompressed, 8.3 keV with 5.36 mJ in 13.8 fs is about 350 GW. On the right is the spectrum fitted at 40.3 eV.

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