ELECTRON BEAM TIMING JITTER AND ENERGY MODULATION MEASUREMENTS AT THE JLAB ERL*

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Abstract

When operating JLab high current ERL a strong reduction of the FEL efficiency was observed with the increase of the average current of the electron beam. Investigating the FEL efficiency drop-off with the electron beam average current we have measured the electron beam phase noise and the fast energy modulations. The phase noise is a variation of the time arrival of the electron bunches to the wiggler. It could be a very effective way of reducing the FEL efficiency especially when the driver accelerator for the FEL is operated with the RMS bunch length of about 150 fs. Under a fast energy modulation we denote a modulation which can not be followed by the FEL due to its time constant, defined by the net FEL gain. Such a modulation also could be a possible cause of the efficiency drop-off. Making the measurements we could rule out the FEL efficiency drop-off due either the fast energy modulation or the phase modulation. We also have learned a lot about instrumentation and techniques necessary for this kind of beam study.

ELECTRON BEAM PHASE NOISE MEASUREMENTS

Investigating the FEL efficiency drop-off with the electron beam average current we have measured the electron beam phase noise and the fast energy modulations. The so-called phase noise is essentially a variation of the time arrival of the electron bunches to the wiggler. That could be a very effective way of reducing the FEL efficiency if one takes in to account that the accelerator is routinely operated with the RMS bunch length of about 150 fs [1]. Under a fast energy modulation we denote a modulation which can not be followed by the FEL due to its time constant, defined by the net FEL gain. Such a modulation also could be a possible cause of the efficiency drop-off. The two effects are strongly connected in the FEL driver accelerator due to the longitudinal phase space transformation, i.e., longitudinal bunch compression. The simplified view of the longitudinal phase space transformation is a rotation of a long and low energy spread beam at the injector by ~90 degrees in the longitudinal phase space so that the bunch length minimum is located at the wiggler [2]. Under such a transformation an energy modulation in the injector would get transferred in to a phase modulation at the wiggler and a phase modulation in the injector would gets transferred in to an energy modulation at the wiggler.

The technique we use for the phase noise characterization of the electron beam was originally developed for noise characterization of ultra fast lasers [3]. It was shown that both phase noise and amplitude noise information can be extracted from the power spectrum measurements of the electron beam intensity. The power spectrum of the electron beam is a comb with spectral lines separated by the frequency of the bunch repetition rate. The envelope of the spectrum is determined by the longitudinal profile of a single bunch. Both the amplitude (AM) and phase modulation (PM) (or noise) of the beam intensity manifest themselves in the power spectrum as the sideband modulations of the spectral lines of the comb spectrum. It was shown in [3] that amplitude of the sideband modulations seen relative to the carrier amplitude changes differently with the harmonic number for AM and PM. The relative amplitude of the sidebands due to the amplitude noise does not change with the harmonic number, whereas the relative amplitude of the phase noise increase as μ^2, where μ is the harmonic number. Thus measurements of the sideband spectrum at the DC contain only the amplitude noise (modulations) and measurements made at very high harmonic number will be dominated by the phase noise (modulations).

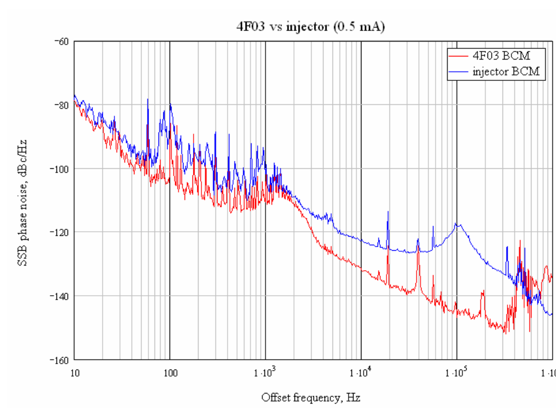

Figure 1a: Single sideband spectrum measured at 0.5 mA.

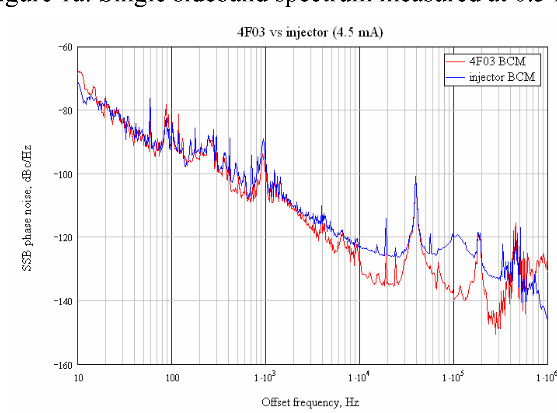

Figure 1b: Single sideband spectrum measured at 4.5 mA.

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Beam current monitor (BCM) cavities and Agilent E5052A Signal Source Analyzer were used for the electron beam phase noise measurements. The BCM is a pill box cavity with the fundamental mode tuned to 1497 MHz. Since the maximum repetition rate of the electron beam is 74.85 MHz the cavity is measuring at least 20th harmonic of the beam. Hence it is reasonable to assume that the sideband spectrum will be dominated by the phase noise. Two cavities used for the measurements are installed at the injector and upstream the wiggler. Signal of such a cavity is strong enough to be used for the phase noise measurements without additional amplification. The E5052A Signal Source Analyzer is a commercially available state of the art device designed for the phase noise measurements of RF sources.

In one set of the measurements the electron beam phase noise was measured as a function of average beam current in the range from 0.5 mA through 4.5 mA. As an example, Fig. 1 shows the phase noise spectra measured at the injector and in the vicinity of the wiggler side by side. Figure 1a shows the spectra measured with 0.5 mA beam current and Fig. 1b shows the spectra measured at 4.5 mA.

Figure 2 shows summary of the measurements made with the BCMs. Most critical question in the data interpretation is the question of the data “pollution” by the amplitude modulation. The signal source analyzer from its operational principal would not distinguish between phase and amplitude modulation. Even when we do the measurements at the relatively high harmonic number due to a very low phase modulation residual amplitude modulation could be present in the signal. We know from beam intensity measurements that there is AM present in the phase noise spectrum we measure and one should keep that in mind when evaluating the measurements results.

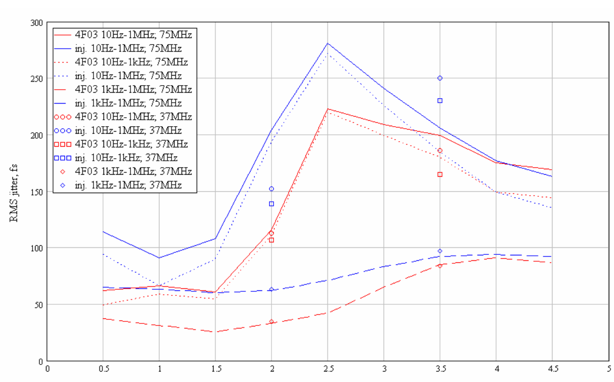
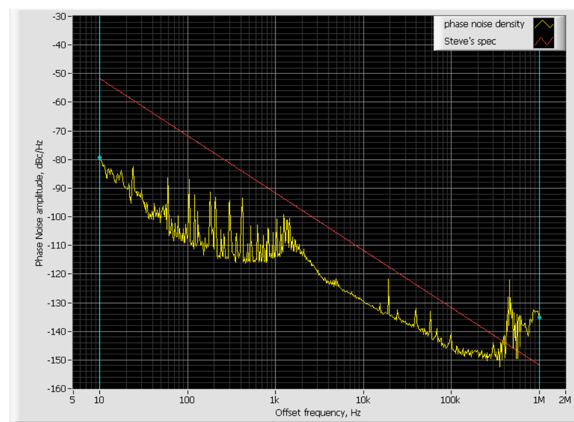


Figure 2: RMS phase noise as a function of the average beam current.

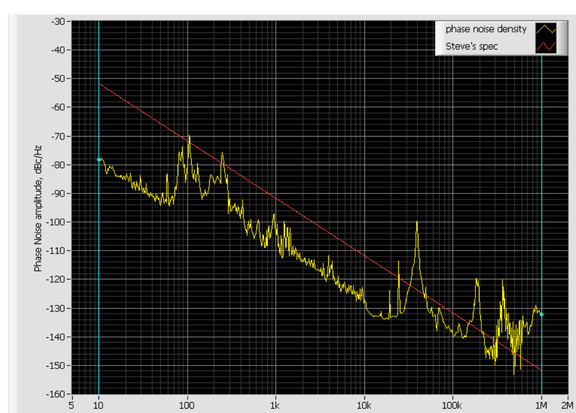
As one sees on the Fig. 2 we did measurements in three different ranges of the offset frequency, namely: 10 Hz ÷1 MHz, 10 Hz ÷1 kHz, 1 kHz ÷1 MHz. There are two reasons for doing the measurement this way. First of all in the preliminary measurements we saw a strong drop of the phase noise at 4.5 mA. On the spectrum one sees that the drop is due to the less noise at low frequency, i.e., below 1 kHz. But the higher frequency components did not went down, and if they reduce the FEL efficiency it could explain why the efficiency did not go up as the RMS jitter went down at the 4.5 mA. That was one reason to separate the range of the phase noise measurements in to two and also make the measurements in the whole range. The other reason is, when looking at the FEL noise data one sees that there are a lot of noise below ~1 kHz and much less above that. This is why we decided to separate the "low" and "higher" frequencies at 1 kHz.

Certainly it is important to compare the measured phase noise (modulation) with the specification. The spec derived from the requirement that the FEL intensity would be reduced not more than by 10 % due to the variation in the electron bunch time arrival can be summarized as following; the RMS jitter at frequency f_m has to be less than $6 \cdot 10^{-9} / f_m$ [4].

Figure 3 shows the comparison of the spec and the measured phase spectra at 0.5 mA and 5 mA. The measured spectra are shown as the yellow curve; the spec is shown as the red line.



(a) measurements at the average current of 0.5 mA



(b) measurements at the average current of 4.5 mA

Figure 3: Comparison of the measured phase noise spectrum with the requirements imposed by the FEL stability.

Comparison of the spec and the phase noise spectrum measured at 5 mA average beam current at first suggests that the measured phase noise exceeds the one allowed by the spec. However it was established that the peaks at ~100 Hz, ~250 Hz and ~ 40 kHz are due to amplitude modulation of the electron beam caused of by the amplitude modulation of the drive laser. The peaks do not represent the phase modulation of the electron beam and therefore our conclusion was that the measured phase noise does not exceed the required one.

ENERGY MODULATION MEASUREMENTS

As was explained above the phase and energy modulation are strongly connected in the FEL driver due to the beam dynamics. Energy modulation can also originate from the LINAC, for instance due to misbehaving RF system. For this reasons we also did measurements of the "fast" up to 1 MHz electron beam energy modulation. The measurements were done at the injector and at the section with dispersion right upstream of the wiggler. Beam position monitors (BPM) were used for the measurements in a combination with the special set of the BPM electronics. The BPM electronics used for the measurements is essentially the analog part of the log-amp based BPM electronics [5], which we have been developing to upgrade our BPM system. The analog part of the electronics was used in a combination with high speed 4 channel simultaneously sampling ADC card. Essential part of the measurements was proper calibration of the electronics and making sure that the electronics will detect the beam position modulation properly. Such tests made in a lab have shown that this type of the BPM electronics would detect the modulation properly, thus our calculation and measurements in the lab were agreed on the 2 % level. The measurements in the lab also have shown that the system noise floor is at the level of 0.5 microns, which we consider to be quite remarkable. Figure 4 shows the lab noise floor measurements of the BPM electronics with the fast ADC. The peak in the X spectrum at the 20 kHz is our artificially introduced test modulation.

Our estimates are that the level of the energy modulation in the injector, which would lead to the phase modulation at the wiggler of a concern level, also would show up as a ~100 μm beam position jitter at the dispersion section in the injector. Thus we would be able to detect such a motion very easily. The first result of the measurements was that there is no significant change in the energy jitter in the injector when the average beam current is increased form 0.5 mA up to 5 mA, so that there is no correlation between the FEL efficiency drop-off and the injector energy modulation. The second result was that beam motion we are measuring in the injector dispersion section is on the level of ~ 1 micron, i.e., much less that the level of concern. The same system was used to measure the fast energy modulations in the dispersion section right upstream of the wiggler. Here again we could not see any dramatic change in the energy modulation with the average beam current. Also the beam energy modulation which we have measured was extremely low and several times smaller that the intrinsic beam energy spread.

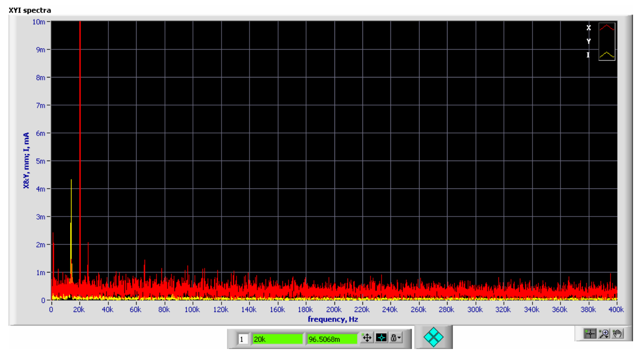


Figure 4: Noise floor in the fast beam position measurements and injected calibration signal.

CONCLUSION

Making the above described measurements we could rule out the FEL efficiency drop-off due either the fast energy modulation or the phase modulation (timing jitter) of the electron beam. We also have learned a lot about instrumentation and techniques necessary for this kind of beam study. We think that it will have an impact not only on our future electron beam diagnostics and instrumentation but also on the instrumentation for other ERL accelerators.

REFERENCES

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