TRANSVERSE COHERENCE PROPERTIES AT FLASH

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Abstract

The detemination of the transverse coherence properties of the FEL beam was the intention of my Summer Student Program at FLASH at DESY, in the group of Ivan Vartaniants. An analysis of coherence measurement on Young's doubles-slit experiment, includes setting up and preparation of a chamber with the double slits, instalation into BL3 at FLASH, taking the measurements, analysis and discussion of results.

1. Mathematical description of Young's double slit experiment

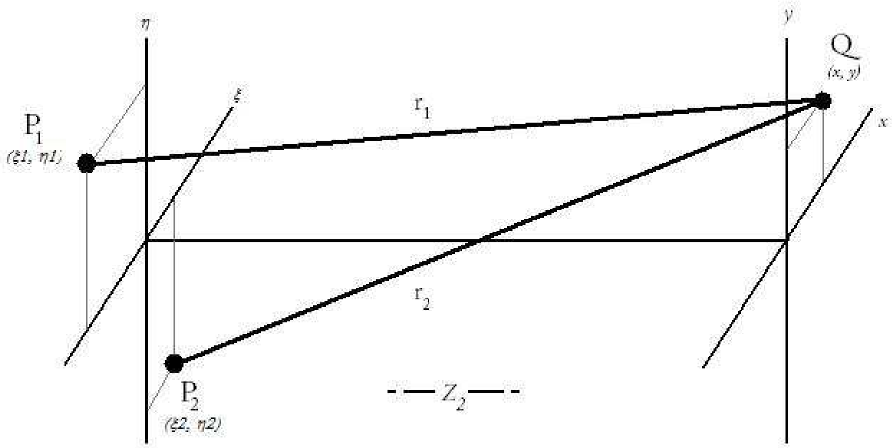

Figure 1: Interference geometry for Young's experiment

The description of diffraction relies on the interference of waves emanating from the same source taking different paths to the same point on a screen. In this description, the difference in phase between waves that took different paths is only dependent on the effective path length. This does not take into account the fact that waves that arrive at the screen at the same time were emitted by the source at different times. The initial phase with which the source emits waves can change over time in an unpredictable way. This means that waves emitted by the source at times that are too far apart can no longer form a constant interference pattern, since the relation between their phases is no longer time independent.

If waves are emitted from an extended source, this can lead to incoherence in the transverse direction. When looking at a cross section of a beam of light, the length over which the phase is correlated is called the transverse coherence length. In the case of Young's double slit experiment, this would mean that if the transverse coherence length is smaller than the spacing between the two slits, the resulting pattern on a screen would look like two single slit diffraction patterns[1].

With a wave source located at a distance z_1 from the double slit and at z_2 distance to the detector ($z_2 << z_1$). The optical axis is aligned with the axis Z, perpendicular to the XY plane as shown in Figure 1.

As the wave source is far away, we assume that it's at infinity and the wavefront is incident parallel to the double slit. In those two slits (P_1 and P_2) it forms two analytical signals without delay. We want to know the intensity at point Q, located at a distance r_1 and r_2 with respect to P_1 and P_2:

$$\mathbf{u}(Q,t) = \mathbf{K}_1\mathbf{u}\left(P_1, t - \frac{r_1}{c}\right) + \mathbf{K}_2\mathbf{u}\left(P_2, t - \frac{r_2}{c}\right) \tag{1}$$

Where K_1 and K_2 are (possibily complex-valued) constants. We know that $I(Q) = \langle u^*(Q,t)u(Q,t)\rangle$ and with some algebra, we get the intensity.

$$I(Q) = I^1(Q) + I^2(Q) + 2K_1K_2Re\Gamma_{12}\left(\frac{r_1 - r_2}{c}\right) \tag{2}$$

Where $\Gamma_{12}(\tau) = \langle u(P_1, t+\tau)u^*(P_2, t)\rangle$ is the mutual coherence function of the light and plays a fundamental role in the theory of partial coherence.

Normalizing the coherence function as follows,

$$\begin{aligned}\tilde{\gamma}_{12}(\tau) &= \frac{\Gamma_{12}(\tau)}{\{\Gamma_{11}(0)\Gamma_{22}(0)\}^{1/2}}\\ \tilde{\gamma}_{12} &= \gamma_{12}(\tau)e^{-i(2\pi\upsilon\tau - \alpha_{12}(\tau))}\end{aligned} \tag{3}$$

Leads us to

$$I(Q) = I^1(Q) + I^2(Q) + 2\sqrt{I^1(Q)I^2(Q)}\gamma_{12}\left(\frac{r_1 - r_2}{c}\right)cos\left(2\pi\upsilon\frac{r_1 - r_2}{c} + \alpha_{12}\frac{r_1 - r_2}{c}\right) \tag{4}$$

After developing algebraic expressions and making further the next geometric approximations

$$\begin{aligned}r_1 &= \sqrt{z_2^2 + (\xi_1 - x)^2 + (\eta_1 - y)^2}\\ r_2 &= \sqrt{z_2^2 + (\xi_2 - x)^2 + (\eta_2 - y)^2}\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta\xi &= \xi_2 - \xi_1\\ \Delta\eta &= \eta_2 - \eta_1\end{aligned} \tag{6}$$

Where $\xi_{1,2}$ and $\eta_{1,2}$ are defined as in Figure 1.
We obtain for the case of a double slit

$$\mathbf{I}(x,y) = I^{(1)} + I^{(2)} + 2\sqrt{I^{(1)}I^{(2)}}\,|\mu_{12}|\cos\left[\frac{2\pi}{\lambda z_2}(\Delta\xi x + \Delta\eta y) + \phi_{12}\right] \tag{7}$$

Where μ_{12} is the complex coherence factor of the light ($0 < |\mu_{12}| \leq 1$), λ is the wavelength of the radiation and the phase difference is ϕ_{12}. $I^{(1)}$ and $I^{(2)}$ are the intensities of each slit

$$I^{(1),(2)} = I_0^{(1),(2)}sinc\left[\frac{a}{\lambda z_2^2}x - \left(\frac{z_1 + z2}{z_1}\right)\xi_{1,2}\right]^2 \tag{8}$$

Where $sinc(x) = \frac{sin(x)}{x}$ [2]

Thus, by measuring the diffraction from a double slit, we are able to infer the degree of coherence $(0 < |\mu_{12}| \leq 1)$ for a given separation.

2. The experiment at the FLASH Facility

Initially, we started with the construction of the chamber in which we introduce a plate with 8 different pairs of double slits with transverse separations between $150\mu m$ and $500\mu m$ in different directions (with a $10\mu m$ slit size), supported with 2 precision motors for precise handling. In the experimental hall at FLASH, the chamber is connected to Beamline 3. It is connected to a pipe of 9.5m (z_2). On the other side of the pipe we connected the other chamber that has inside the detector. This particular detector is a new kind of experimental detector, the pnCCD [4].

The vacuum subjected to both chambers was about $10^{-7} mbar$, the FEL wavelength was 13.5nm, the distance between slits and source was 70m.

During the week of testing assigned, there were difficulties with the detector. At the end of the week we took the first measurements that in principle were correct, but a later analysis revealed that they were only correct for one tansverse direction and not the other, due to issues with the detector readout.

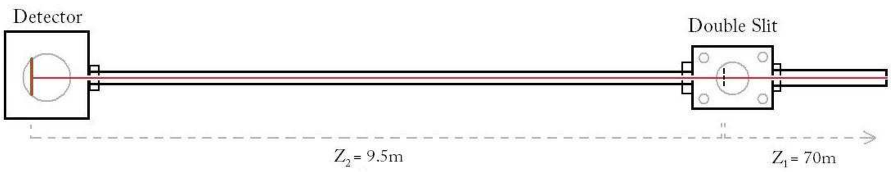

Figure 2: Outline of experiment

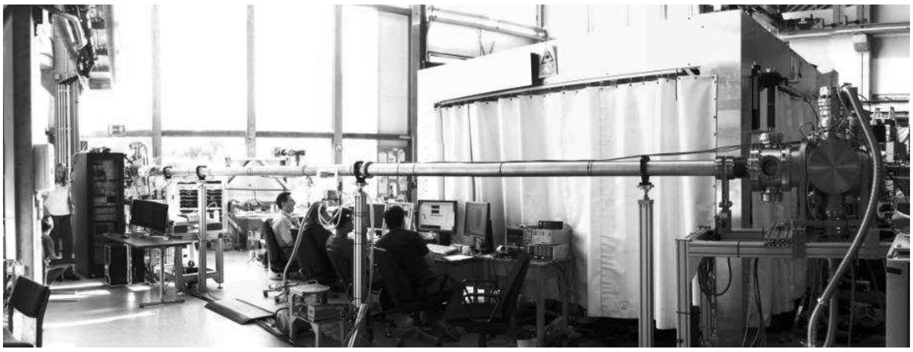

Figure 3: Experimental Hall at FLASH

3. Data analysis

Data from the detector were directly treated by running Matlab programs developed specifically for coherence evaluation.

At first we obtained the images of the diffraction patterns which have been treated by removing the corresponding noise signal, and aligned them as closely as possible with the axes X and Y. Due to the manufacturing process of the slits they are not fully aligned and this is important for a good analysis.

We can see in the pictures (Fig. 4 and Fig. 5) the data that corresponds to samples with a separation of $150\mu m$ and $300\mu m$ respectively.

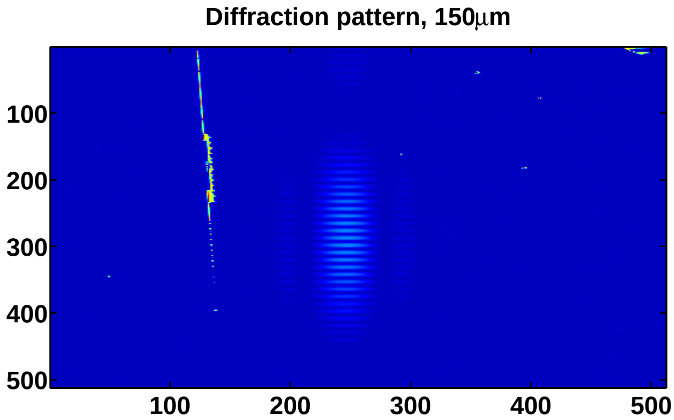

Figure 4: Diffraction pattern obtained with a slit pair separated by $150\mu m$

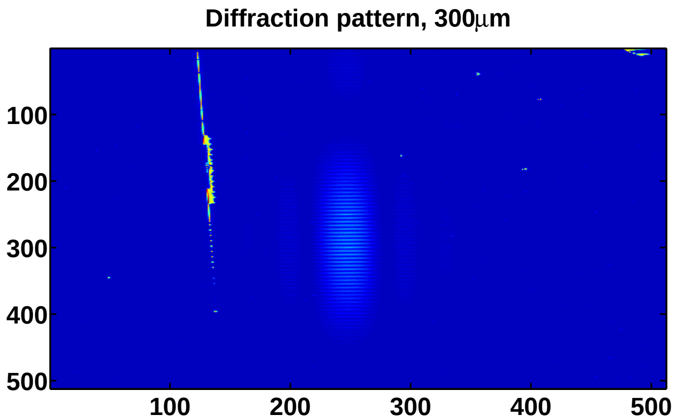

Figure 5: Diffraction pattern obtained with a slit pair separated by $300\mu m$

Subsequently, an analysis is performed for 3 contiguous columns of pixels producing plots as shown in Figures 6 and 7. In black is shown the experimental measurement and in red the fit. Fitting software is run that retunrs a number of parameters ranging from the intensity and the actual size of the Slits and most importantly, the coherence factor.

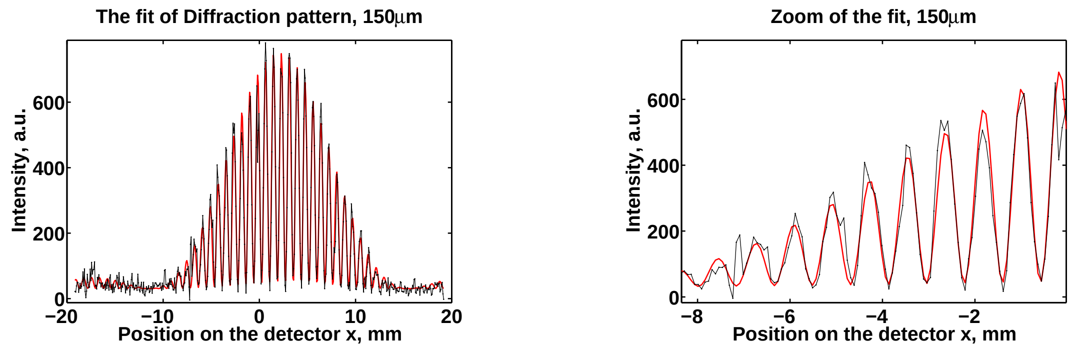

Figure 6: Fit of the diffraction pattern and zoom, $150\mu m$. Black data, red fit.

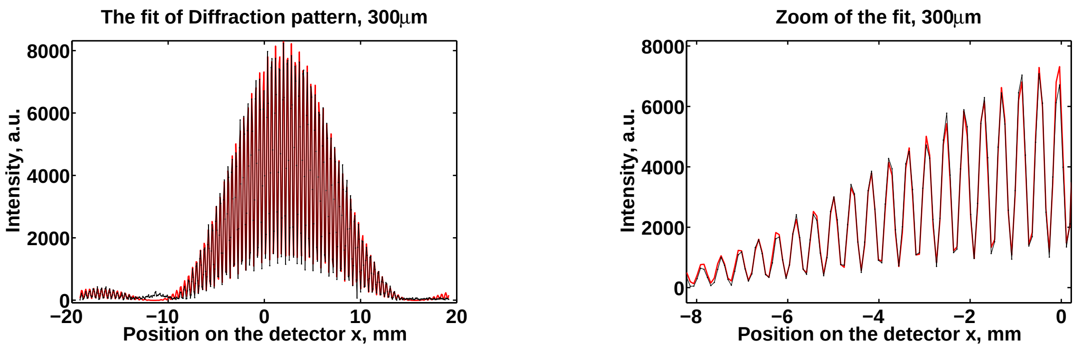

Figure 7: Fit of the diffraction pattern and zoom, $300\mu m$. Black data, red fit.

In these particular cases we obtain for the $150\mu m$ case, values for the separation of slits of $150.7\mu m$ with a size of $9.9\mu m$ and a value of the coherence factor of **0.94**. In the case of the $300\mu m$ slits, values of $301.6\mu m$ slit separation and $9{,}3\mu m$ size were found with a value of coherence factor of **0.76**.

As it can be seen, the smaller the separation between slits the better the value of the coherence factor. **1** corresponds to perfect coherence. This leads us to seek what the behavior of the coherence factor is as function of the separation between slits (d), represented in the following graph (Fig. 8) for the cases of 150, 300 and $350\mu m$.

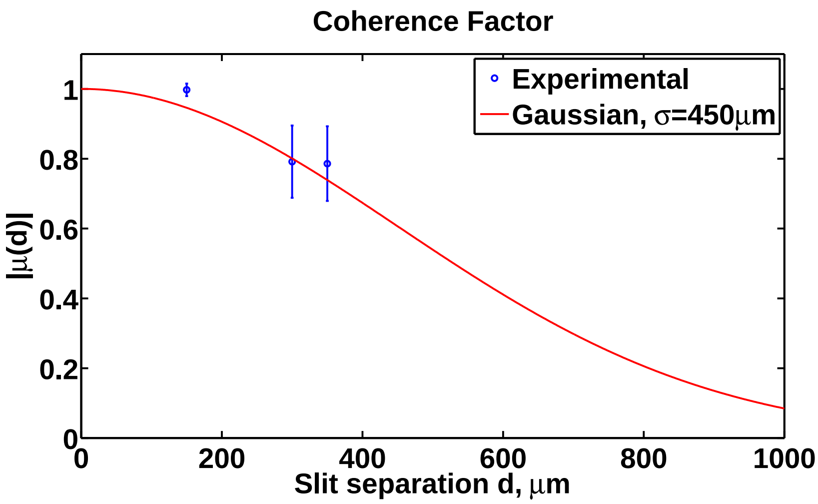

Figure 8: Modulus of the complex coherence factor in the vertical direction

The larger the separation, the larger the uncertainty. I attempted to use the data from samples of $400\mu m$ but their quality was poor and could not make a good fit. We find to a reasonable aproximation that the coherence length, σ, is aproximately $450\mu m$ in this case. With same as yet unquantified uncertainty.

Finally we proceeded with the sample of $250\mu m$ of separation and was positioned in different parts of the beam (49 positions) to verify that the coherence factor does not change. An analysis of the data led us to the conclusion that the detector doesn't measure with the precision needed to verify this phenomenon. We are, however, able to study the beam intensity at different positions with the following results (Figs. 9, 10 and 11).

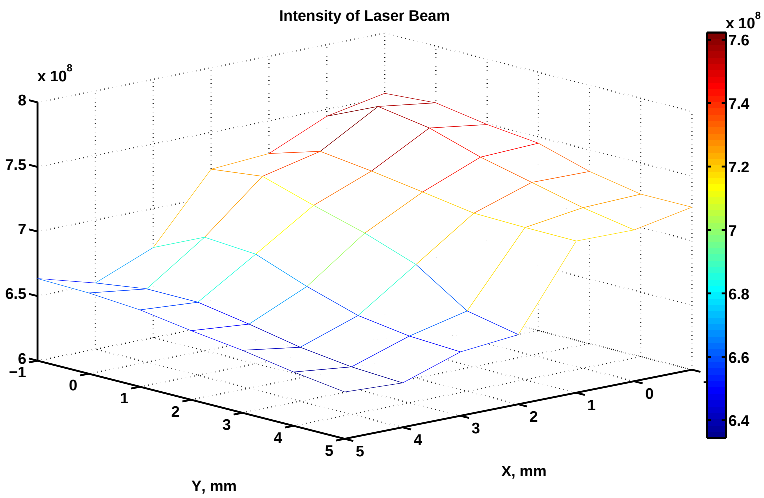

Figure 9: 2D surface plot of average intensity at BL3 beamline

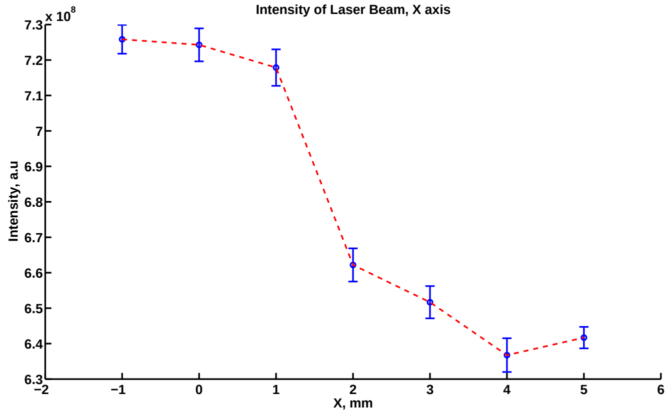

Figure 10: Laser Beam in X axis

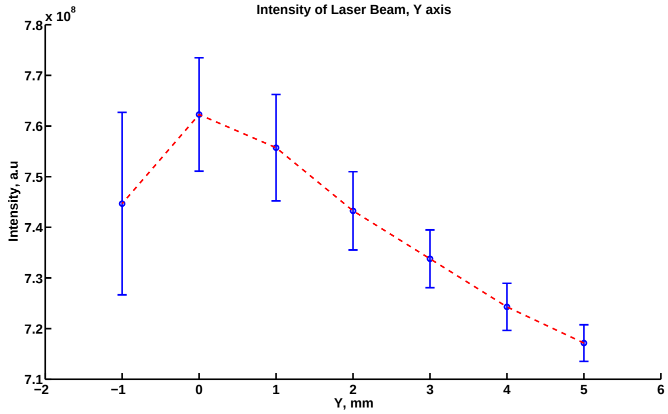

Figure 11: Laser Beam in Y axis

4. Conclusions

We hve presented the results of measurements of the transverse coherence at FLASH. We were only able to properly analyze the measures in one transverse direction, due to detector issues. Despite limitations of the detector, the data obtained be interpreted to describe the coherence of FLASH.

It was relatively easy to analyze the small slit separation data, however, for large separations it is complicated to the point of almost impossible to analyze properly. This is to be improved when the detector is working at full capacity. During this experiment, we only used one of four CCDs chips, with both new hardware and software. Using the detector completely (the four CCD as one) with all hardware functioning to specification will allow better signal to be measured, and hence more readily interpretable results.

5. References

[1] Wikipedia article about Diffraction.(http://en.wikipedia.org/wiki/Diffraction)

[2] J.W. Goodman, Statistical Optics, (Wiley, New York, 1985).

[3] Diferents Journals about Transverse-Coherence Properties of the Free-Electron-Laser.

[4] W. Leitenberger, et al, J. Synchrotron Rad. (2008). 15, 449-457