Measurements of second- and higher-order intensity correlation functions (so-called Hanbury Brown and Twiss experiment) were performed at the free-electron laser (FEL) FLASH [1]. We demonstrated the high transverse coherence properties of the FEL beam with the degree of transverse coherence about 80% and degeneracy parameter of the order 10^9 that makes it similar to laser sources. Intensity correlation measurements in spatial and frequency domain gave an estimate of the FEL average pulse duration of 50 fs. Our measurements of the higher-order correlation functions indicate that FEL radiation in the non-linear regime of its operation obeys Gaussian statistics that is characteristic to chaotic sources.

The core idea of the HBT experiment [2,3] is to perform a coincidence measurement of the normalized second-order intensity correlation function at two separated points r_1 and r_2

\[ g^{(2)}(r_1, r_2) = \frac{\langle I(r_1)I^*(r_2) \rangle}{\langle I(r_1) \rangle \langle I(r_2) \rangle}, \]  

(1)

where \( I(r_1) \) and \( I(r_2) \) are intensities of the wavefield. The averaging in equation (1) is done over a large ensemble of different realizations of the wavefield. It is well established that chaotic light can be described in the frame of Gaussian statistics [4] and is completely determined by the first-order correlation function known as a complex degree of coherence \( \gamma(r_1, r_2) \). The intensity correlation function then reduces to [5]

\[ g^{(2)}(r_1, r_2) = 1 + \frac{\tau_c}{T} |\gamma(r_1, r_2)|^2. \]  

(2)

Here \( \tau_c \) is the coherence time of the wavefield and \( T \) is the time resolution of the detectors, or pulse duration. By definition the CDC \( |\gamma(r_1, r_2)| \leq 1 \) and the intensity correlation function \( g^{(2)}(r_1, r_2) \leq 2 \). The contrast of \( g^{(2)}(r_1, r_2) \) in Eq. (2) is proportional to the ratio \( \tau_c/T \), or to the inverse number of longitudinal modes \( M_T = T/\tau_c \) for chaotic sources.

FEL sources, with pulses of few tens of femtoseconds, are ideally suited for intensity correlation measurements. According to FEL theory [6] these sources should obey Gaussian statistics in the linear and deep non-linear regime of operation. In these conditions the correlation function \( g^{(2)}(r_1, r_2) \) should have the form of Eq. (2) and provide an access to the transverse coherence properties of an FEL.

The experiment was carried out at FLASH (PG2 beamline) that was operated with six undulator modules and a total undulator length of 30 m. The electron bunch charge was 600 pC, and the electron energy 1.08 GeV resulting in a photon wavelength of \( \lambda = 5.5 \) nm. The average photon pulse energy was about 110 \( \mu \)J, which corresponds to about 3\( \times 10^{12} \) photons per pulse at this photon energy. A monochromator comprised of a plane grating, collimating, and focusing mirrors, and an exit slit with variable slit width was utilized to modify the bandwidth.

The normalized second order correlation function \( g^{(2)}(x_1, x_2) \) for a bandwidth of 0.8\( \times 10^{-4} \) is shown in Figures 1 (a,c). Remarkably, it reaches the maximum value of two at small separations (Figure 1 (c)). This indicates that the contrast is close to one which is significantly higher than at
synchrotron sources [7], where it was not exceeding 0.3. An analysis of \( g^{(2)}(\Delta x) \) as a function of the separation \( \Delta x=x_2-x_1 \) around the center of the beam provided the value of a transverse coherence length \( l_c=0.93\pm0.04 \) mm. This value is substantially larger than the measured beam size in horizontal direction (0.45 mm (FWHM)) that indicates high coherence of the beam. We quantified it by evaluating the degree of coherence \( \zeta [6] \) and obtained the value \( \zeta=0.78\pm0.01 \) that is in a good agreement with the Young’s measurements at FLASH [8]. Importantly, counting the total flux on the detector we can estimate the degeneracy parameter, which is the number of photons in a single mode. Our estimates give a value above \( 10^9 \) that is significantly higher than at any synchrotron sources.

![Figure 1: Intensity correlation analysis. (a, b) Intensity correlation function \( g^{(2)}(x_1, x_2) \) for a bandwidth of 0.8·10^{-4} (a) and 1.4·10^{-3} (b). (c, d) Intensity correlation function \( g^{(2)}(\Delta x) \) taken along the white line in (a,b). The bandwidth and the degree of transverse coherence are indicated. Insets in (c, d) show intensity fluctuations, or the function \( g^{(2)}(x, x) \) taken along the blue line in (a, b). In these plots for visibility each 5-th point is indicated as a circle. The error bars in (c,d) are obtained by statistical analysis of 20 individual sub-ensembles (10^3 shots each) from the whole set of 2·10^4 shots.](image)

The second order correlation function \( g^{(2)}(x_1, x_2) \) for a bandwidth of 1.4·10^{-3} is shown in Figures 1 (b,d). A larger bandwidth is equivalent to a shorter coherence time, and the values of \( g^{(2)}(x_1, x_2) \) are reduced as expected from equation (2). For the large bandwidth we observed (see Figure 1 (d)) that the correlation function \( g^{(2)}(\Delta x) \) has second maximum at a larger point separation. This behavior can be due to the contribution of two independent sources in the lasing conditions of FLASH.

References