Dispersion effects on performance of the free-electron laser FLASH

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This paper studies the impact of transverse dispersion on the free-electron laser (FEL) performance in two main aspects: radiation power sensitivity to electron beam energy offset and radiation wavelength spectrum. Since these issues are related to electron trajectories, studies on the FEL power dependence to the beam orbit are also presented. The experiments were done at the free-electron laser in Hamburg (FLASH). A method to measure and control the dispersion is also described.

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I. INTRODUCTION

Dispersion is the momentum dependence of charged particle deflections in a magnetic field. The change of horizontal offset and angle at position $s$ due to an energy change at an upstream position $s_0$ can be written in second order as

\[
\Delta x_D(s) = D_x(s_0, s)\delta(s_0) + D_{xx}(s_0, s)\delta^2(s_0)
\]

\[
\Delta x_D'(s) = D_x'(s_0, s)\delta(s_0) + D_{xx}'(s_0, s)\delta^2(s_0),
\]

where $\delta(s_0)$ is the initial relative momentum of the electron ($\delta = \Delta p/p$), and $D_x(s_0, s)$, $D_x'(s_0, s)$, $D_{xx}(s_0, s)$, and $D_{xx}'(s_0, s)$ are the first- and second-order horizontal dispersion functions from $s_0$ to $s$. A method to measure and correct the dispersion and its implementation at the free-electron laser in Hamburg (FLASH) is presented in Sec. II.

In free-electron lasers (FELs) there is a constructive interference between the fields radiated by the different electrons of the bunch, so that FELs produce radiation with full spatial coherence (i.e. laserlike) of a brilliance several orders of magnitude higher than that of conventional synchrotron radiation facilities. An FEL can amplify an input seed signal or the spontaneous radiation produced by the shot noise. In the last case, FEL radiation is obtained by the self-amplified spontaneous emission (SASE) process [1,2]. Detailed information about FEL theory can be found in [3–5].

The FEL process requires high electron beam intensities (i.e. small beam sizes, small emittances, and high currents) and an extremely small energy spread. In addition, the FEL process depends strongly on a good transverse overlap between the electron and the photon beam. As a consequence, the deviation of the electrons with respect to the design trajectory must be stringently controlled. Studies on the FEL power dependence to the electron beam trajectory at FLASH are presented in Sec. III.

In the presence of dispersion, energy jitter in the accelerating sections converts into electron trajectory jitter which distorts the FEL performance. Studies on the FEL power dependence to the electron beam energy offset for different dispersion scenarios at FLASH are presented in Sec. IV.

In general, the longitudinal slices of the beam that produce FEL radiation have different energies. Without dispersion, all slices follow the same trajectory and can potentially radiate. With dispersion, slices with a momentum offset travel off axis so that they do not generate FEL radiation. In most cases the presence of dispersion reduces the total FEL power (fewer slices radiate) and narrows the radiation spectrum (only the on-momentum slices radiate). Studies of the impact of dispersion on the SASE spectrum are presented in Sec. V.

A. FLASH

FLASH, based on the TESLA Test Facility [6,7], is a user facility at DESY and a pilot facility for both the European X-ray Free-Electron Laser (XFEL) [8] and the International Linear Collider (ILC). It generates SASE-FEL radiation with a wavelength ranging from the vacuum ultraviolet to the soft x-ray regime. FLASH demonstrated SASE operation at a wavelength of 32 nm in 2005 [9], at 13 nm in 2006 [10,11], and at 6.5 nm (design value) in 2007 [12].

A schematic layout of FLASH is shown in Fig. 1. FLASH operates in pulsed mode with a macropulse repetition rate of up to 5 Hz. Each macropulse is 0.8 ms long. Within each macropulse there can be up to 800 bunches separated by 1 μs.

Electron bunches are generated in a laser-driven rf gun with a nominal bunch charge of 1 nC. Six TESLA accelerating modules, each of them containing eight superconducting cavities, accelerate the beam to energies of up to 1 GeV. This maximum energy corresponds to a radiation wavelength of 6.4 nm. A further energy upgrade was done in late 2009.

To reach the peak current necessary for the SASE process, the electron bunches are longitudinally compressed in two bunch compressor chicanes. The first bunch compressor...
sor (BC2) [13] is located after the first accelerating section ($E = 127$ MeV) and can reduce the bunch length by up to a factor of 10. The second bunch compressor (BC3) [14] is placed after the accelerator modules ACC23 ($E = 450$ MeV) and can further compress the beam by about a factor of 4. In total, the bunch compression system of FLASH can reduce the initial bunch length after the gun of 2 mm down to 50 \(\mu\)m (rms values), corresponding to a final design peak current of 2.5 kA. A third-harmonic cavity which will optimize the longitudinal compression was installed in late 2009.

After the modules that provide the final acceleration ($E = 1$ GeV) there is a collimation section that protects the undulator from radiation damage. This is done by removing electrons with energy deviation larger than \(\pm 3\%\) and with large betatron amplitudes [15].

The undulator section consists of six permanent magnet undulators with a length of 4.5 m each. The gap is fixed at 12 mm, the peak magnetic field is 0.486 T, and the undulator length is \(\lambda_u = 27.3\) mm [16]. A pair of quadrupoles placed between each of the six modules provides the focusing required to keep the beam size in the whole section both small and constant as possible.

A dipole magnet after the undulator section deflects the electron beam into a dump [17], while the FEL radiation propagates to the experimental hall. In order to facilitate machine commissioning and to perform accelerator component experiments, the beam can bypass the collimator and undulator sections.

FIG. 1. (Color) Schematic layout of FLASH (not to scale). Total length is about 250 m. The elements shown include acceleration structures (yellow), FEL undulators (magenta), and main dipole magnets (blue).

FIG. 2. (Color) Electron beam properties at the undulator entrance obtained from start-to-end simulations. Only the part marked by the magenta dots produces FEL radiation.
B. FEL simulations with GENESIS 1.3

To study the impact of transverse effects on the FEL performance, it is necessary to use a three-dimensional time-dependent FEL program. GENESIS 1.3 [18] has been used for the simulations presented in this paper.

The electron beam properties at the undulator entrance along the longitudinal position of the bunch are shown in Fig. 2. They were obtained from start-to-end simulations done for FLASH at 495 MeV and 0.85 nC using CSRTRACK [19] for the bunch compressors and the collimator section and ASTRA [20] for the remainder of the lattice.

II. DISPERSION MEASUREMENT AND CORRECTION AT FLASH

A. Dispersion measurement

Dispersion measurement is based on measuring the trajectory for different energies of the beam, obtained by changing the gradient of the different accelerator modules in the machine (ACC1, ACC23, and ACC456). The horizontal and vertical orbit changes downstream of the rf section are, to second order,

\[
\Delta x(s) = D_x(s_0, s) \delta(s_0) + D_{xx}(s_0, s) \delta^2(s_0),
\]

\[
\Delta y(s) = D_y(s_0, s) \delta(s_0) + D_{yy}(s_0, s) \delta^2(s_0),
\]

where \( \delta \) is the relative momentum (or energy) deviation induced in the accelerator module at position \( s_0 \) and \( s \) the position of any other beam position monitor (BPM) after that. Figure 3 displays an example of a dispersion measurement for a single BPM.

In our case the linear dispersion functions (\( D_x \) and \( D_y \)) are defined as the first-order coefficients of the second-order polynomial fit. This way, the slope at \( \delta = 0 \) is obtained—instead of the slope of the whole set of data that would be obtained doing a linear fit. The interest is focused on measuring and correcting the dispersion close to \( \delta = 0 \), since the total energy range for the dispersion measurement is usually significantly bigger than the energy spread of the beam.

Uncertainties in the dispersion measurement include both statistical and systematic errors. The statistical error depends on the trajectory uncertainties, the total energy range of the measurement, and the number of steps into which the measurement is divided. For typical measurement parameters statistical uncertainties are usually in the order of 1–3 mm. Systematic errors are dominated by BPM calibration errors and are estimated to be about 6%.

B. Correction algorithm

Both orbit and dispersion are corrected using correction coils and quadrupole movers in the undulator and collimator sections. The optimal settings are calculated using the orbit and dispersion response matrices, the terms of which are defined as the shift of the orbit or dispersion due to a change of the corrector strength:

\[
OR_{i,j} = \frac{\Delta u_i}{\Delta \Theta_j} \quad DR_{i,j} = \frac{\Delta D_i}{\Delta \Theta_j},
\]

where \( \Delta u_i \) and \( \Delta D_i \) are the change of the orbit and the dispersion at the BPM \( i \), and \( \Delta \Theta_j \) is the change of the strength of the corrector \( j \).

The algorithm consists in finding a setting of correctors \( \Delta \Theta \) which induces some orbit and dispersion that minimizes in a least squares sense the difference between the final orbit and the dispersion with respect to some desired values (i.e. with respect to the golden values):

\[
(1 - w) \| \tilde{u}_{\text{meas}} - \tilde{u}_{\text{gold}} \|^2 + w \| \tilde{D}_{\text{meas}} - \tilde{D}_{\text{gold}} \|^2 = \text{min},
\]

where the subindex “meas” refers to the measured values and the subindex “gold” refers to the final desired orbit and dispersion. \( w \) is a factor between 0 and 1 that defines the relative weight for the orbit and the dispersion correction.

In addition to correctors coils which simultaneously change both trajectory and dispersion, two quadrupoles in the collimator section (Q3/5ECOL) can be used to modify the horizontal dispersion downstream of the collimator.

C. Dispersion tool at FLASH

Based on the procedure described above, a software application to measure and correct both the orbit and the dispersion has been developed at FLASH. Using this application, the dispersion measured from all accelerator modules (ACC1, ACC23, or ACC456) can be kept below 5 mm (rms) in both planes. This limitation stems from the
dispersion measurement error (usually between 1 and 3 mm) and the response matrix errors.

Figure 4 shows an example of a dispersion measurement and a correction in the vertical plane. The beam energy was varied in ACC456. The dispersion in the undulator was corrected while keeping the orbit constant. The rms dispersion was reduced from 17 to 4 mm after four iterations.

More details about dispersion measurement and correction at FLASH can be found in [21].

III. SASE SENSITIVITY TO ELECTRON TRANSVERSE TRAJECTORY

The FEL power sensitivity to the incoming electron beam trajectory was measured at FLASH. For this purpose, the launch angle of the beam into the undulator was varied by \( \pm 0.1 \) mrad. The beam charge was 0.80 nC and the beam energy was 450 MeV. Measurements for H19SEED were repeated on another day when the beam energy was 495 MeV and the charge was 0.85 nC.

Figure 5 shows results of the measurements and simulations. The relative FEL power for the different kicks is indicated. Each measurement is the result of averaging over 100 shots. The maximum SASE energy was about 20 \( \mu \)J on the first measurement day and 50 \( \mu \)J on the second measurement day measured by a microchannel plate (MCP)-based photon detector [22,23]. As can be seen in the figure, measurements for the horizontal plane done on the two different days show a good reproducibility.

Simulations were done using the electron beam properties plotted in Fig. 2 as an input. In the simulations the maximum SASE macropulse energy is about 30 \( \mu \)J. There is a good agreement between measurements and simulations in the horizontal plane. In the vertical plane, there is a good agreement for moderate kicks (i.e. in the range of \( \pm 30 \) mrad).

As can be seen in Fig. 5, the FEL intensity is more sensitive to the vertical trajectory than to the horizontal one in both the measurements and the simulations: the measured width of the curve (FWHM) is 100–105 mrad for the horizontal plane and 90 mrad for the vertical one. This is because the wiggling movement of the electrons in the undulator takes place in the horizontal plane. Moreover, the additional natural focusing of the undulator in the vertical plane contributes to this bigger sensitivity of SASE energy to the vertical trajectory.

IV. SASE SENSITIVITY TO ELECTRON BEAM ENERGY OFFSET

A. Measurements

To study the impact of dispersion on FEL power sensitivity to the electron beam energy jitter, the SASE macropulse energy was measured for different dispersion scenarios as a function of the beam electron energy offset.

Figure 6 shows measured dispersion from ACC456 in the undulator BPMs for the different dispersion conditions. In order to introduce additional horizontal dispersion, the current of the quadrupole magnets in the collimator section (Q3/5ECOL) was changed. The collimator quadrupole currents were adjusted to correct the horizontal dispersion and the vertical steers from upstream of the dogleg up to the seed section were changed to correct vertical dispersion.
Figure 7 shows the measured SASE energy as a function of electron energy offset for the different dispersion scenarios. The initial electron energy was 495 MeV and the electron charge was 0.85 nC. The plotted SASE energies are averaged over 100 shots. Although units were chosen arbitrarily to make the comparison easier, maximum SASE macropulse energy was similar in both cases: 49 $\mu$J before dispersion correction and 40 $\mu$J afterwards (measured by the MCP detector). The different electron beam energies were obtained by changing the gradient of the accelerator modules ACC456.

Table I shows a summary of the experimental results. After dispersion correction, the range in which the radiation wavelength can be tuned by simply changing the electron beam energy was increased: the wavelength could be tuned (without losing more than 50% of the radiation power) by simply changing the ACC456 gradient within a range of ±1.64% for the initial conditions and up to ±3.44% after dispersion correction.

### B. Simulations

Time-dependent simulations of these measurements were performed with GENESIS 1.3. Only the initial case and the situation after dispersion correction in both planes were considered. The input electron beam used in the simulations has the characteristics shown in Fig. 2.

For the GENESIS calculations, the energy and the energy distribution of the incoming bunch were left untouched. The simulations of the off-energy points were done by scaling all magnetic fields in the undulator region, calculating the change in orbit launch from measured dispersion and changing the optics parameters of the bunch to account for the fact that for the experiment the strength of the focusing elements between the rf section and undulator was not adjusted. Scaling the undulator fields shifts the radiation wavelength, but the shift is well inside the bandwidth in which GENESIS computes the FEL power.

Figure 8 shows measured and simulated SASE energy versus electron beam energy deviation. A good agreement is observed, showing the increase of the FWHM of the SASE energy distribution in terms of $\delta$ when the dispersion is corrected.

Table I. Summary of measurements on SASE energy sensitivity to relative electron beam energy offset.

| Condition                      | $D_x$(RMS) | $D_y$(RMS) | FWHM in $\delta$ |
|--------------------------------|------------|------------|------------------|
| Initial measurement            | 22 mm      | 30 mm      | 0.82%            |
| $D_x$ generated                | 48 mm      | 28 mm      | 0.74%            |
| $D_x$ corrected                | 12 mm      | 31 mm      | 1.06%            |
| $D_x$ and $D_y$ corrected      | 11 mm      | 5 mm       | 1.72%            |

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**FIG. 6.** (Color) Measured dispersion in the undulator for the different conditions.

**FIG. 7.** (Color) Measured SASE energy as a function of electron energy offset ($\delta = \Delta p/p_0$) for the different dispersion scenarios.

**FIG. 8.** (Color) Measurements and simulations of SASE energy as a function of electron energy offset before and after correction.
of the electron slices which produce FEL radiation.

FIG. 9. (Color) Energy and current distribution along the bunch of the electron slices which produce FEL radiation.

V. DISPERSION IMPACT ON THE SASE SPECTRUM

Figure 9 shows the energy and the current along the bunch obtained from start-to-end simulations for the electron slices that produce FEL radiation (see also Fig. 2). As illustrated in the figure, there is an energy variation along the bunch of about 3 MeV which causes the beam slices to produce FEL radiation with different wavelengths.

Without dispersion, the trajectory is the same for all the particles, so all the slices produce FEL radiation. Dispersion causes trajectory deviations of the slices depending on their energy. As a consequence, dispersion can prevent some of the beam slices from radiating (depending on the dispersion magnitude and on the nominal energy). In general, dispersion reduces the total FEL power (less beam slices radiate), makes the radiation spectrum narrower, and chooses its central wavelength (only the slices with certain energy radiate).

As presented later in this section, measurements showed that the impact on the spectrum can be different depending on the dispersion sign. The effect of the dispersion depends on the initial transverse coordinates along the bunch. In order to understand this, the results of simulations with an artificial beam under different initial conditions are discussed in the following subsection.

A. Simulations with a Gaussian electron beam

The input beam used in the simulations has the following characteristics: (i) bunch length of 300 μm (rms); (ii) Gaussian current profile with a maximum current of 1.5 kA and cut at both sides at 500 A; (iii) energy variation with a positive slope of ±1% along the bunch, with the center of the beam with a design energy of 495 MeV; (iv) constant values along the bunch for the rest of the parameters: transverse emittance of 2.0 μrad, slice energy spread of 0.5 MeV (rms), matched optics corresponding to 495 MeV, and 11.5 T/m of gradient for the quadrupoles in the undulator.

We study the impact of $D_x$ together with a horizontal offset $x$. The analysis can be easily generalized to the other transverse coordinates. Three dispersion scenarios are analyzed: no dispersion and positive and negative linear dispersion of 50 mm. All the shown simulated spectra are averaged over 40 shots. The impact of introducing dispersion is analyzed for different initial horizontal offset distributions along the bunch: initial constant offset along the bunch (zero and nonzero), initial linear correlation between $x$ and energy, and initial quadratic correlation between $x$ and energy.

1. Initial constant offset along the bunch

The impact of the dispersion depends on the value of the initial transverse positions. For zero transverse offset (see Fig. 10) without dispersion, the whole beam radiates. Introducing dispersion prevents the lasing of the slices with more energy deviation (head and tail of the bunch) resulting in a narrowing of the wavelength spectrum. Because of the symmetry in this case, the central wavelength does not change after adding the dispersion.

If the initial offset of the beam is nonzero, the final central wavelength depends on the dispersion sign. In the example shown in Fig. 11, the initial offset is +100 μm. Positive dispersion results in an increase of central wavelength and negative dispersion in its reduction. The total radiation power decreases in both cases.

If the initial offset of the beam is big enough, the introduction of dispersion can increase the FEL power. In the example in Fig. 12 (in which the initial offset is 250 μm), the initial beam almost does not radiate. The introduction of positive dispersion improves the trajectories for the tail of the bunch (lower energy, longer $\lambda$), so that it generates more radiation. Negative dispersion leads to a stronger radiation of the head (higher energy, shorter $\lambda$).

2. Initial linear $x$-energy correlation

Assuming that the centroid offset is corrected, the central wavelength is not affected when dispersion is introduced. Positive and negative dispersion will have a different impact depending on the initial $x$-energy correlation. In the particular example of Fig. 13, there is a positive initial correlation of 2 cm. The introduction of 5 cm of dispersion adds up to a final $x$-energy correlation of 7 cm. As a consequence, the head and the tail generate less FEL radiation and the final spectrum becomes narrower.

On the other hand, subtracting 5 cm of dispersion implies that the beam has a final correlation of −3 cm, which slightly decreases the FEL power and narrows the spectrum in comparison to the initial situation. A subtraction of
FIG. 10. (Color) Dispersion effects on the wavelength spectrum for an initial zero offset along the bunch.

FIG. 11. (Color) Dispersion effects on the wavelength spectrum for an initial offset of 100 μm along the bunch.

FIG. 12. (Color) Dispersion effects on the wavelength spectrum for an initial offset of 250 μm along the bunch.
2 cm exactly counteracts the initial correlation, which results in an increase of the FEL power and in a widening of the wavelength spectrum (not shown in Fig. 13).

3. Initial quadratic x-energy correlation

In a situation with initial quadratic x-energy correlation, the introduction of additional dispersion narrows the spectrum and changes the central wavelength which gets bigger or smaller depending on the dispersion sign (see Fig. 14). In this particular example of a negative parabola, positive dispersion decreases the central wavelength, while negative dispersion increases it. Both positive and negative dispersion reduce the radiation power.

4. Summary

The introduction of (linear) dispersion adds a (linear) correlation between transverse coordinates and energy to the bunch. The effect of the dispersion will be different depending on the initial transverse coordinates of the slices along the bunch. Table II summarizes the results presented in this subsection.

| Initial condition        | FEL power and spectrum width | Central wavelength |
|--------------------------|-----------------------------|--------------------|
| Zero offset              | ↓                           | =                 |
| Moderate offset          | ↓                           | ↑ or ↓ b           |
| Big offset               | ↑                           | ↑ or ↓ b           |
| Linear correlation       | ↑ or ↓ a                    | =                 |
| Quadratic correlation    | ↓                           | ↑ or ↓ b           |

aDepending on the final correlation.
bDepending on the dispersion sign.

FIG. 13. (Color) Dispersion effects on the wavelength spectrum for an initial linear x-energy correlation.

FIG. 14. (Color) Dispersion effects on the wavelength spectrum for an initial quadratic x-energy correlation.

TABLE II. Dispersion impact on the wavelength spectrum for different initial transverse offsets.
B. Measurements

The SASE radiation spectrum was measured with the FLASH spectrometer [24] for different horizontal dispersion scenarios. The current of the quadrupoles in the collimator section (Q3/5ECOL) was modified for this purpose. The beam charge was 0.85 nC and the electron energy was 495 MeV. The trajectory was kept constant in all cases, for which small displacements of the quadrupoles were sometimes necessary.

According to simulations done with the measurement optics, a 1% increase of the Q3/5ECOL current generates about 10 mm rms dispersion in the undulator section. Figure 15 shows the measured spectra for the different dispersion conditions. Every measurement is the result of averaging the spectrum over 200 shots. The radiation power is maximum when the dispersion is zero (\( \frac{\lambda}{C^2} \)) measured by the MCP detector). The introduction of dispersion results into a decrease of the FEL power. The central wavelength depends on the sign of the generated dispersion: it becomes longer for an increase of the Q3/5ECOL current and shorter when the current of Q3/5ECOL is reduced. According to the analysis of the previous subsection a trajectory offset or angle, or a second-order correlation between \( x \) (or \( x' \)) and energy at the undulator entrance is necessary to explain these results.

C. Realistic simulations

The cases without dispersion and with changes of Q3/5ECOL of ±1.5% were simulated. Electron beam properties obtained at the entrance of the undulator from start-to-end simulations were used as an input for GENESIS 1.3 (see Fig. 2). For the different simulation conditions, the trajectory changes due to dispersion were added to the initial coordinates. For each slice \( i \),

\[
x(i) = x_0(i) + D_x \delta(i) \quad x'(i) = x'_0(i) + D'_x \delta(i). \tag{5}
\]

Optics changes were taken into account, assuming that the beam was perfectly matched in the initial case. Possible electron intensity changes due to the modification of Q3/5ECOL current were not considered.

Figure 16 shows the horizontal offset and angle along the bunch with and without dispersion (for ±1% change in the Q3/5ECOL current). As can be seen from the figure, the initial horizontal offset is quadratically correlated to the energy between \( \xi = 385 \) μm and \( \xi = 400 \) μm. This contributes to explaining (according to Sec. VA) why the central wavelength depends on the dispersion sign. In addition, an initial centroid trajectory offset of 50 μm and an angle of −20 μrad at the entrance of the undulator were assumed.

Figure 17 shows the simulation results. The simulated spectra are the average results over 100 seeds. A qualitative agreement between measurements and simulations is observed. An increase of the Q3/5ECOL field decreases the FEL power for longer wavelengths.
and a decrease of the Q3/5ECOL field decreases the radiation intensity for shorter wavelengths. In any case, the introduction of dispersion reduces the total SASE power. The main difference between measurements and simulations is the spectrum width which was bigger during the measurements. This can only be explained if the real electron beam distribution had more energy chirp than the obtained in the start-to-end simulations.

VI. CONCLUSION

In Sec. IV it has been shown that by correcting the spurious dispersion inside the undulator region, the SASE power jitter due to electron beam energy fluctuations is decreased. In other words, when dispersion is corrected there is a reduction of the undulator orbit launch sensitivity to the energy jitter. As a consequence, the beam operation is more stable and the tolerances for the rf amplitude and the phase jitter can be more relaxed, and the radiation wavelength can be tuned in a wider range by simply changing the electron beam energy.

In Sec. V it has been proven that dispersion correction allows having a broader radiation spectrum and avoids a reduction of the FEL power due to the off-axis trajectories of the slices with an energy deviation with respect to the nominal one. If very small bandwidth is required, removing dispersion is not always desired.

Moreover, it has been shown that dispersion can be used to tune the central wavelength of the FEL spectrum, the shift of which depends on the energy chirp of the electron beam distribution. However, it is advisable to correct all the dispersion and to tune the wavelength by simply modifying the electron energy. This way, lasing will be more stable and the radiation power will be higher.

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