MEASUREMENT OF ADVANCED DISPERSION-BASED BEAM-TILT CORRECTION

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Abstract

Free electron lasers in the X-ray regime require a good slice alignment along the electron bunch to achieve their best performance. A transverse beam slice shift reduces this alignment and spoils projected emittance and optics matching. Coherent synchrotron radiation, specifically for over-compression going through full compression, and transverse wakefields are major contributors to this. In the case of the large-bandwidth operation, with a strong energy chirp on the bunch, this misalignments furthermore reduce the spectral bandwidth of the FEL pulse. Well-defined manipulation of dispersion allows to compensate for this slice centroid shifts, therefore enhancing lasing power and in case of the large bandwidth mode, spectral bandwidth. This work shows the first application of this correction on an X-ray FEL resulting in increase in beam-power and bandwidth.

INTRODUCTION

This paper discusses an improved version of the proposed dispersion-based beam-tilt correction scheme presented here [1], as well as experimental results measured at LCLS [2]. This is the first application of the dispersion-based beam-tilt (centroid slice shift) correction in a running FEL facility.

Short gain-lengths require good overlap of the electrons and its radiation field. Transverse oscillations of the electron beam reduce said overlap and over-all radiation power. Oscillations of the entire bunch lead to uniform lasing suppression [3]. A centroid shift along slices of the bunch, beam-tilt, leads to non-uniform lasing suppression. Thereby only some of the slices undergo transverse oscillations and lasing suppression. This is deliberately used in several applications [4] to shorten the photon pulse.

Common, unwanted sources of beam-tilt are transverse wakefields and coherent synchrotron radiation. Whereas the last is of special importance when over-compressing the beam. Over-compression is done by flipping the energy chirp in the 4 dipole chicanes. The longitudinal wakefields of the downstream cavities will further increase the flipped energy chirp. The strongly chirped electron beam results in an increased photon bandwidth. Use-cases of such beam include Bragg imaging [5] and single-shot absorption spectroscopy [6] to name a few. Simulations showed a much stronger beam-tilt for over-compression. In the presence of a strong energy chirp the beam-tilt not only leads to lower power but also smaller bandwidth. This obstructs the large-bandwidth operation mode, where the bandwidth is of crucial importance.

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THEORY

This section outlines the advanced dispersion-based beam-tilt correction concept as well as its differences to the classical correction scheme. To do so we introduce the nomenclature of bunch and lattice dispersion. Bunch dispersion is a beam parameter where the linear term is defined by $\eta_x = \langle \delta x \rangle / \langle \delta^2 \rangle$ (Derivations in presence of higher orders are covered in [1]). This correlation is directly related to the beam-tilt and does not influence lattice dispersion, which is a pure lattice parameter. It is defined as R_{16} between two points along the beam-line [7]. Note that a change in lattice dispersion will always influence beam dispersion, but not vice versa.

The classical dispersion-based beam-tilt correction (described in [1]) relies on the fact that beam-tilt and beam dispersion are correlated at places with a strong energy chirp. Minimizing the beam dispersion by manipulating the lattice dispersion corrects also for the beam-tilt. Once the beam tilt is corrected and the energy chirp is removed (eg by following linac) it is independent from purely transverse manipulations (Quadrupole magnets in non-dispersive sections). This corrects for the projected emittance increase and the partial lasing suppression through centroid slice offset in the undulator.

Energy jitter at the dispersion knobs will translate into orbit jitter downstream. The energy jitter of the LCLS copper linac [8] led to measured strong shot-to-shot fluctuations in FEL power. This problem only grows more important in machines with worse energy stability, which makes it necessary to correct for both lattice dispersion and beam-tilt for optimal performance. Manipulation of the lattice dispersion at places with different energy chirp achieves this, since the relation of beam-tilt and bunch dispersion depends on the energy chirp. This has the downside of doubling the minimal required dispersion knobs from two to four. This is due to the fact that, like for the beam-tilt correction, two knobs are needed to correct for lattice dispersion in momentum and space. It is furthermore necessary to take into account the position of the jitter source with respect to the correction knobs.

SETUP

This section outlines how the proposed correction is implemented in LCLS. The FEL is driven by a 2.856 GHz linac with an 11.414 GHz linearizer. The electron beam is compressed by two 4 dipole chicanes of which both are equipped with a pair of tweaker quads to close dispersion. Operational parameters used for this experiment are expanded upon in the next section and a more detailed overview of LCLS is found

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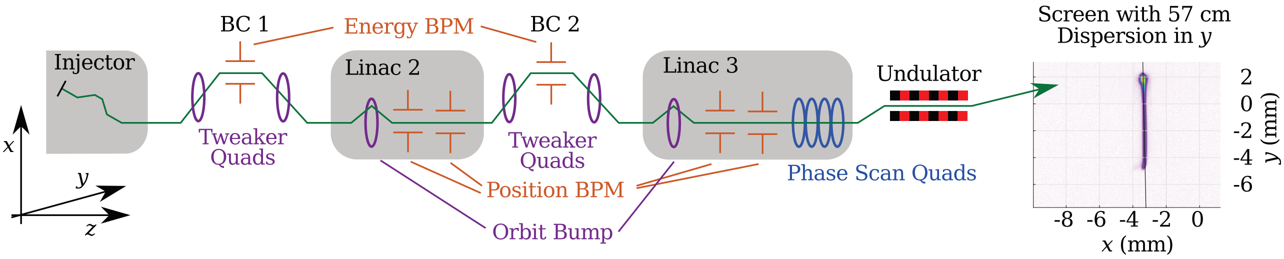

Figure 1: Schematic drawing of the dispersion-based beam tilt correction. Energy and position BPMs are used to measure the lattice dispersion. The profile monitor in the dispersive section (orthogonal to the correction plane) measures the bunch dispersion. Reconstruction is done by scanning the phase advance between correctors and measurement point. The correction of both needs four dispersion knobs which can consist of any combination of orbit bumps and quadrupoles in high dispersive sections.

in [2, 9]. Figure 1 shows a systematic sketch to measure and correct the beam tilt.

The lattice dispersion can be measured by beam position monitors (BPM). This experiment followed the common method to measure lattice dispersion by correlating obit to energy. The bunch position, measured by several BPMs, is correlated to energy, measured beam synchronous by a BPM in a dispersive section. The reconstruction of the lattice dispersion in momentum and space requires to measure the orbit at several locations along the beam-line. Resolution was increased by raising the energy jitter by scanning the RF amplitude around the working point.

The beam-tilt on the other hand requires the measurement of the transverse to longitudinal correlation. To do so the beam was first streaked, for example by a transverse cavity. Due to not having this possibility available this was done indirectly by dispersion and a strong energy chirp at the spectrometer after the undulator line. The correlation is then recorded with a profile monitor (100 µm YAG screen). To increase resolution lasing was suppressed by creating a vertical orbit offset within the undulator. The known vertical dispersion and linear longitudinal phase space correlation [10] allowed to transform the measured value into beam-tilt. To measure the bunch dispersion in both momentum and space the phase advance between correction knob and screen is scanned by quadrupole magnets located within the third linac. This has the limitation that beam tilts originating after the phase advance scan are not recorded anymore. The shown setup allows to measure absolute beam-tilts. To reduce error sensitivity the perturbation method explained here [1] was used, which only requires relative beam-tilts.

The basic correction scheme needs a pair of dispersion knobs, separated by ideally 90° phase advance to correct for the beam-tilt. The advanced scheme needs an additional pair of correctors to simultaneously minimize for the lattice dispersion. This experiment used two kinds of dispersion knobs. The first one is a pair of quadrupole magnets within one of the dispersive sections of the two bunch compressors. In LCLS the quadrupole magnets are separated by roughly 70° phase advance and the beam size is dominated by dispersion at their location. Both bunch compressor tweaker quads were successfully used for orbit correction.

The second method is a three corrector orbit bump to manipulate lattice dispersion [11]. This has the benefit to manipulation the dispersion with lower optics perturbation as the method introduced before as the orbit bump does not influence the optics. Rematching of the beam is still necessary due to the changed projected spot-size. This point is void if the beam was matched to the slice which was not the case here.

RESULTS

The proposed correction method was benchmarked using the over-compression mode. Due to the over-compression, the energy chirp changes sign. Instead of canceling the chirp the longitudinal wake fields further increase it. This allows to increment the energy chirp of the electron beam without expanding the slice energy spread, which in terms allows a very broad photon bandwidth. One of the limiting factors of this operation mode are beam-tilts originating from over-compression due to Coherent Synchrotron Radiation. This operation mode therefore benefits most of the proposed correction.

The final beam energy for the experiment shown here was 13.7 GeV with a bunch-charge of 190 pC and a peak current of 3 kA. The tails of the electron beam were truncated within the first bunch compressor [**?**]. The electron energy spread is 1% from tail-to-tail. The measured projected emittance in both planes at first bunch compressor was 450 nm. The FWHM photon pulse length was as low as 25 fs.

Figure 2 shows beam tilts recorded both prior and after a correction. Vertically the images correspond to a phase advance scan between profile monitor and correction source. The scan shows a clear reduction of the beam-tilt. In this experiment the beam-tilt and the lattice dispersion were corrected iteratively, which therefore leads to both small residual beam-tilt and lattice dispersion.

The tuned-up initial photon beam power was 45 GW prior to the application of the correction. After three consecutive rounds of correction of both beam-tilt and lattice dispersion the beam power was more than doubled to 100 GW. The

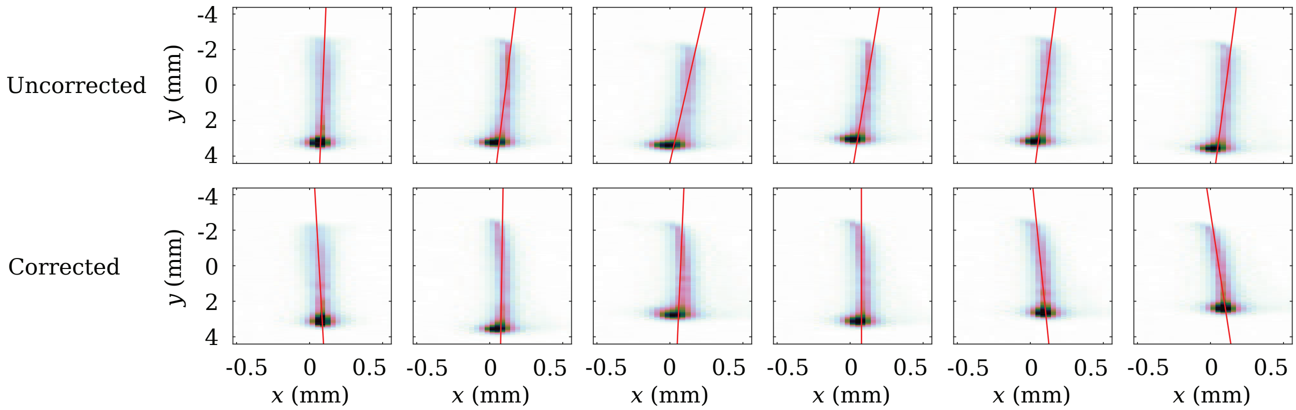

Figure 2: Over-view of corrected and uncorrected beam tilts at various phase advances. Note that the beam-tilt was not perfectly corrected since this scheme aims at an combined correction of lattice dispersion and beam-tilt correction. This are recorded beam-tilts after a final lattice dispersion correction iteration.

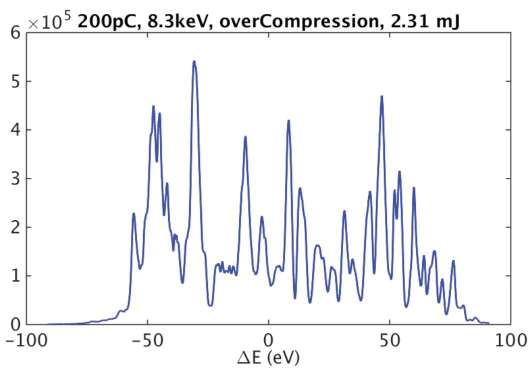

Figure 3: Recorded photon spectrum. Since the photon bandwidth exceeds the spectrometer acceptance we can only show a lower limit of the recorded photon bandwidth.

beam-tilt correction specifically benefits the tails as introduced in the last section. It therefore further increases the bandwidth. The measured bandwidth after correction was bigger than the spectrometer acceptance. We can therefore only give a lower limit of the measured bandwidth with 1.3% FWHM. This corresponds to the highest ever measured bandwidth at LCLS [12]. The spectrum of a typical shot is shown in Figure 3.

CONCLUSION

This work implements the proposed correction [1] and further expands on it to correct for both beam-tilt and lattice dispersion simultaneously. The resulting doubling of the lasing power and increase of photon bandwidth shows the effectiveness of the correction. The fact that this was the largest measured bandwidth at LCLS only highlights this point. The improved version specifically took into account shot-to-shot energy jitter, by reducing residual lattice dispersion, which is of special importance for normal conducting linacs.

The correction concept in the current form is however still limited as it needs several hours to setup. While the beam-tilt correction runs by a script, a lot of the lattice dispersion correction is hard to automate. Furthermore is the measurement of the bunch dispersion limited to over-compression due to the reliance on dispersion-based streaking. This limitations is void in machines with direct transverse streaking capabilities (eg. a transfers deflector followed by a profile monitor in a non-dispersive section). Future experiments aim at reactivating an installed S-Band deflector after the second bunch compressor.

In practice it might be sufficient to reduce the number of dispersion knobs and only correct for most of the tilt, thus saving considerably in setup time.

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