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# FLEXIBLE OPERATION MODES FOR EUXFEL

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*Abstract*

A major challenge in single-linac-multiple undulator setups like EuXFEL is generating individually shaped photon pulses for each of the undulator lines, especially when working in an operation mode where a single pulse train, or cw stream, feeds all undulator lines. This work presents the experimental verification of a flexible delivery scheme feeding all three undulator lines of EuXFEL with electron bunches individually shaped in charge, compression and optics from a single RF pulse burst.

## SETUP

European XFEL (EuXFEL) consists of a single linac which feeds three undulator lines. All undulator lines are fed in parallel, receiving electron pulses that originate from RF pulse trains with a repetition rate of 10 Hz. Each pulse train consists of up to 2700 pulses with a maximal repetition rate of 4.5 MHz. A beam distribution system with a fast and a slow kicker system distributes the pulses between the three undulator lines. The fast kicker system works on a bunch-to-bunch rate and is used to dump superfluous pulses as well as to create soft-kicked pulses for lasing suppression in the fresh-bunch [1, 2] setup. The slow kicker system is used to distribute the beam into one of the two undulator branches.

In most operation modes, the first part of each RF pulse train is used to stabilize the beam through transverse and longitudinal intra-train feedbacks and then dumped after the linac without passing any undulator lines and subsequently not producing any X-rays. The next part of the train is sent in bulk towards the first undulator line (Fig.1, colored in purple). The following part is dumped again in order to provide a transition time (about 30 μs) which is required to relax the slow kicker of the beam distribution system. The last part of the pulse train is used to deliver pulses to two undulator lines that follow one another (Fig. 1, colored in blue and green). Each of the three lines is operated exclusively by allowing the lasing only in one line while suppressing it in the other two. To maximize the available RF time for each experiment, the two serial undulators receive bunches in an interleaved mode. In summary, there are two undulator lines which receive beam in an interleaved mode with a maximum repetition rate of 4.5 MHz and one undulator line which is separated by about 30 μs from the other lines. The repetition rate and number of pulses at each undulator line can be lowered by dumping individual pulses in the linac dump.

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## METHODS

We investigated two options to shape the duration of pulses within a single pulse train, which is necessary to provide pulses of different durations for each of the undulator lines. The first option is to exploit the gun laser system, which consists of an acoustic-optical modulator (AOM) in front of the amplifier [3,4]. This system is designed to keep the charge constant along the entire pulse train, however, this system is also able to create pulses of varying charge along the pulse train. The achievable charge profiles along the pulse train underlie only two limitations. First, the charge cannot be larger than what the laser pulse allows for an unattenuated pulse. Second, there have to be high charge pulses in regular intervals to prevent building up an inversion state in the laser gain medium. Since the AOM is able to react at a 4.5 MHz scale, this system is able to customize the bunch length for all three undulator lines even if the two serial undulator lines are operated in an interleaved mode.

The second option for longitudinal shaping along the pulse train is to use the RF system, which allows to modulate both amplitude and phase of wave in the cavity along the pulse train [5, 6], thereby effectively changing the energy chirp and thus compression of the beam. The maximal frequency of transitions between different states depends on the characteristics of the klystron as well as the quality factor of the super-conducting RF cavity and allows for different compression states for different sections of the pulse train, but not for the individual pulses of the train. Therefore, this option is only suitable when the undulator lines are operated in a non-interleaved mode.

These two options are not exclusive. Combining the two techniques allows to operate with lower charge while still correcting the compression setting individually for optimal performance of all undulator lines. Furthermore, there is the possibility to use multiple RF flat-tops in phase and amplitude in the gun to correct for the different space charge in the low energy regime and thus improve the optical mismatch by exposing the electron to a different electric field.

## RESULTS

Reducing the charge is the most flexible way to reduce the pulse duration. It allows for nearly full flexibility of the pulse patterns within a pulse train. Unfortunately, changing the charge leads to different effective compression given similar RF settings, which in turn leads to a miscompressed beam as shown in Fig. 2. It is important to note that the increase in electron pulse duration does not necessarily transfer to the photon pulse, which could still be significantly shorter due

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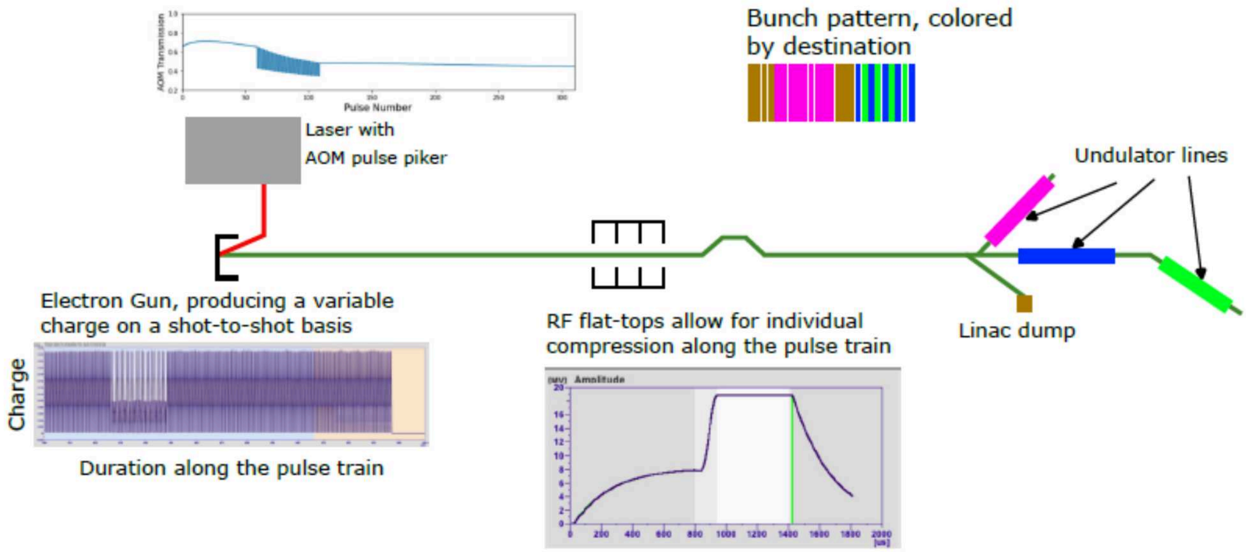


Figure 1: Schematic layout of EuXFEL with its pulse trains feeding three undulator lines. The laser AOM absorber located close to the electron gun allows to arbitrarily shape the charge profile. The modulated RF flat-top allows for different compression along the pulse train. Note the different time scales of the two options making them appropriate for different delivery modes (depending on destination).

to non-linear compression of the beam. However, it does lead to quite non-uniform lasing along the pulse.

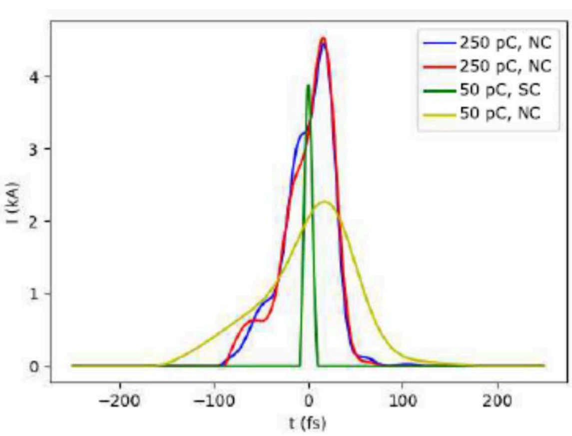


Figure 2: Temporal reconstruction of the electron beam using the CRISP spectrometer [7] for different charges and compressions. Here, NC (nominal compression) is optimized for 250 pC and SC (short-pulse compression) is optimized for 50 pC. Note that a lower charge with non-optimized compression can lead to longer electron pulses.

We did several measurement campaigns for both hard and soft X-rays showing that the variable charge setup without compression didn't have any effect on any of the other beam lines. Furthermore, no cross-talk between beam lines was observed when utilizing non-linear and nominal compression in an non-interleaved operation mode. Figure 3 demonstrates this for both altered compression as well as charge. A soft X-ray measurement campaign during an experimental user delivery run shows that indeed lowering the charge results in shorter photon pulse duration (Table 1). A more targeted effort would likely result in higher intensities.

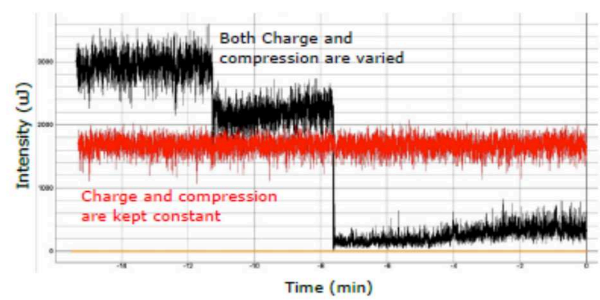


Figure 3: Intensity of two beamlines in parallel operation. The black beamline is tuned in both charge and compression while the red beamline is kept constant and does not experience any cross-talk from the other beamlines effort.

Lowering the charge also benefited extreme non-linear compression cases. Even though non-linear compression had already been implemented in the past for all three undulator lines and was used for a user delivery for hard X-rays, such extreme cases always showed increased intensity fluctuations. Furthermore, the compression feedbacks were hard pressed to keep the condition over the entire 4 days of user delivery. The combination with lower charge allowed to stabilize the intensity jitter and operate in a more stable compression regime in general. Combining reduced charge of individual pulses with altered compression along the pulse train proved to be reliable and stable over a 16h run. During this time we were able to run all feedbacks including the

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| Charge (pC) | Intensity (µJ) | Estimated photon duration | Stability |
|---|---|---|---|
| 250 | 5000 | 16 fs | |
| 200 | 4600 | 14 fs | 95% |
| 150 | 3200 | 11 fs | 94% |
| 100 | 2300 | 8 fs | 92% |
| 75 | 1600 | 6.5 fs | 92% |
| 50 | 500 | 5 fs | 89% |
| 50* | 800 | 4.8 fs | 83% |
| 30* | 400 | 3.6 fs | 89% |
| 20* | 200 | 2 fs | 81% |

Table 1: Results from a single beam time at 1 keV. The top values correspond to non-adjusted compression whereas for the bottom ones (with *) the compression was adjusted. The photon pulse duration was estimated utilizing the photon spectral analysis to measure the photon group duration.

transverse and longitudinal intra-train feedbacks, stabilizing both the pointing as well as the arrival time of the photon beam with this operation mode. Furthermore, the combination of those two techniques allowed for significantly shorter pulses. In the extreme case of 15 pC this resulted in 1% of single spike events at 1 keV. Specific optimisation of this mode remains for future exploration. Some exemplary spectra are shown in Fig. 4.

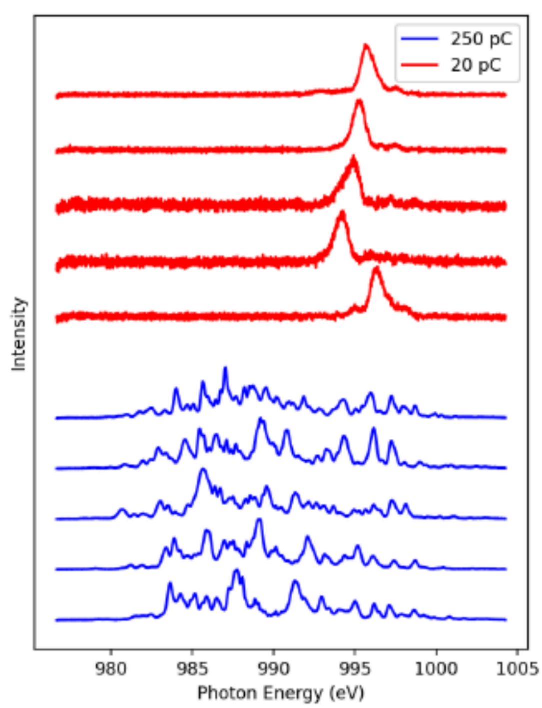


Figure 4: Selected photon spectra for both nominal (250 pC) and low charge (20 pC) with optimized compression.

We also studied the possibility to use different gun RF flat-tops in phase and amplitude to correct for the different space charge and thus matching condition. The optical mismatch due the altered charge was not too severe to hinder beam transport or significantly deteriorate beam quality, with the obvious exception of the optical mismatch itself. However, this mismatch was corrected for in front of each of the undulator lines, thereby allowing for full flexibility. The additional complexity of the operation mode therefore outweighed its benefits.

## DISCUSSION

The proposed methods allow for additional operational flexibility at the EuXFEL with its several undulator lines fed by a single linac. It offers pulse length control on a shot-to-shot (4.5 MHz) level as well as a higher flexibility for a different flat-top configuration. In principle, this method can be used complementary to other methods like fresh-slice [8–10], enabling more stable operation. These results might be of interest for the community since they offer an easily implementable way to shape the pulse duration in single linac-multiple undulator line settings, given that several facilities with with this layout will be commissioned in the near future.

## ACKNOWLEDGEMENTS

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