

# OPTICS & COMPRESSION SCHEMES FOR A POSSIBLE FLASH UPGRADE

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## Abstract

The proposed FLASH upgrade will rely on high quality electron beams provided to all undulator beam lines. Here we describe possible modifications to the FLASH lattice and the compression scheme that aim at improving the beam quality and the ability to control critical beam properties along the machine — simultaneously and independently for all beam lines.

## INTRODUCTION

FLASH, a “Free eLectron LAsEr in Hamburg” is a user facility for ultra bright light pulses in the vacuum ultra violet (VUV) and soft X-ray wavelength regime [1, 2]. The currently covered wavelength range is from 60 nm to 4.2 nm. The accelerator serves two free electron laser (FEL) beam lines, FLASH1 and FLASH2. FLASH1 is equipped with fixed gap undulators of about 30 m length while FLASH2 has variable gap undulators of about the same length [3]. This implies that a FLASH1 wavelength change requires a change of the global beam energy, while at the same time at FLASH2 this energy change is not needed and even unwanted, and is thus a major cause of set up time for transition between experiments. The user facility FLASH is in operation since 2008 but the FLASH1 undulators have been installed already in the times of the TTF2 test facility and need to be replaced by variable gap undulators. A major upgrade is currently planned to significantly improve the FEL performance and operability of FLASH. Moreover a slight energy upgrade will be achieved by replacing two old accelerating modules by new ones with higher average gradient and thereby increasing the final energy from 1230 MeV to 1350 MeV. To cover the aimed spectral range of 60 nm down to 3 nm in the fundamental for SASE operation in FLASH2 beam line [4], two energy setpoints are foreseen: one setpoint at medium energy of 750 MeV and one at the highest possible energy of 1350 MeV.

The two FEL beam lines will be modified to facilitate modern FEL modes (FLASH1: external seeding, FLASH2: harmonic lasing, self-seeding, etc.). A key prerequisite to these advanced lasing schemes is high quality electron beam. This article highlights the modifications of the bunch compression schemes required to provide such beams.

## LATTICE MODIFICATIONS

As mentioned above, two accelerating modules will be replaced with new ones with higher accelerating gradient (see Fig. 1). This leads to a 100 MeV higher energy setpoint than before: i.e. 550 MeV for the second bunch compression

chicane (BC). The two modules are located between the first and the second BC. They are equipped with a single quadrupole each instead of the quadrupole doublet of the current modules.

The beam from the photo injector is extremely cold. Such cold beams are explicitly prone to coherent synchrotron radiation (CSR) and longitudinal space charge (LSC) driven micro bunching instabilities. It is assumed that high quality beams imply that micro bunching effects are to a large extent precluded. I.p. seeded FEL operation requires a laser heater (LH)[5]. Thus in the current design a LH, which is capable of generating an energy modulation of up to 35 keV, will be located upstream of the first BC. The required space for the LH implementation is realized by moving the first BC downstream by a couple of meters and shortening its downstream matching section.

Reducing the  $R_{56}$  (longitudinal dispersion) of the first BC to about 50 mm would symmetrize the constraints on amplitude and phase errors for minimal timing and compression jitter [6]. However, even with a third BC installed, the compression factor of the first BC has to be between 4 – 10 (see Table 2) to obtain the required peak currents. On the other hand, reducing the  $R_{56}$  at constant compression and energy implies a larger chirp and nonlinearity from the upstream RF-module, and thus increased amplitude of the 3rd harmonic longitudinal linearizer ACC39. We could however reduce the bend angle of the 1st BC from  $18^\circ$  ( $R_{56} \sim 180$  mm) to  $16^\circ$  ( $R_{56} \sim 140$  mm) within the current vacuum chamber and in the limits of the ACC39 amplitude. The section between the 1st BC and the second acceleration section will be dedicated to matching of the transverse envelope from the injector into the regular lattice. This includes four screen station for measuring the mismatch and the projected beam emittance. In order to accommodate measurement *and* matched beam transport in the shortened beam line, the optics has to be switchable between measurement mode and transport mode.

The second BC will be converted from an s-type (6 dipoles) chicane to a c-type (4 dipoles) chicane with almost the same bend angle  $5^\circ$  ( $R_{56} \sim 75$  mm). Thereby a couple of meters are freed to implement a multi quadrupole scan matching section for the transverse envelopes.

The lattice of the main linac (four modules) remains unchanged.

The FLASH1 beam line will not have any dogleg until downstream of the undulators. The FLASH2 beam line will keep its current extraction arc with a global horizontal angle of  $12^\circ$ . Each FEL beam line will be equipped with a third independent c-type BC. This is advantageous because firstly the final compression (almost full compression) is applied at highest possible beam energy, and secondly (in the case of FLASH2) because the final compression is applied

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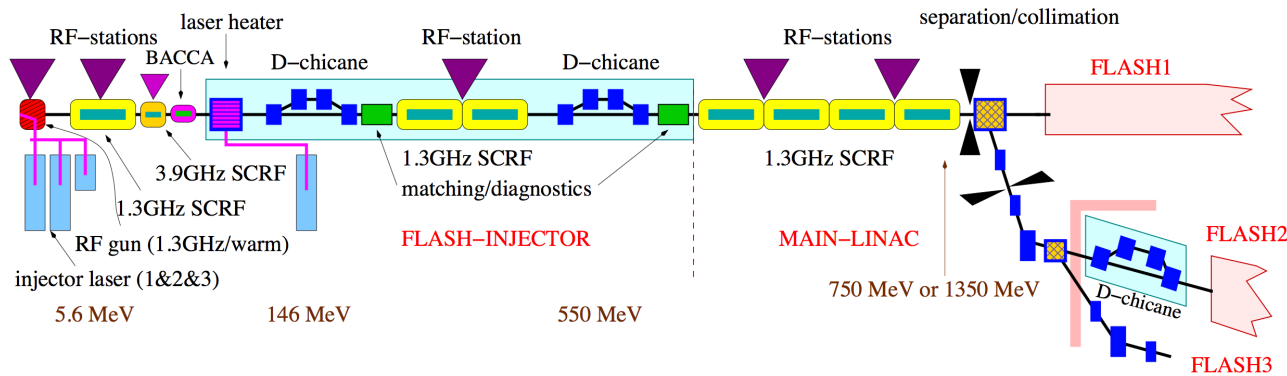


Figure 1: Layout of FLASH up to the FEL beam lines with the planned modifications. The stretch inside the light blue boxes and the FEL beam lines FLASH1 ( see [7, 8]) and FLASH2 (see [9]) in the red boxes will be redesigned.

downstream of the extraction arc. That reduces the influence of space charge (SC) and CSR effects on the bunch because of the larger rigidity of the beam at higher energies. For the time being the new BCs are simulated assuming an bend angle of  $4.7^\circ$  ( $R_{56} \sim 25$  mm). For a more detailed description of the upgrade plans see [7].

## START TO END SIMULATION

We perform start-to-end simulations to estimate the possible electron bunch parameters which are obtainable. For the simulations the ASTRA tracking code [10] for the first 3 m and for the adjacent part of the simulation of the accelerator XTRACK [11] is used. XTRACK has implemented a three-dimensional Poisson solver in the bunch frame and a one-dimensional projected model for the CSR wake field and are included in the simulations as well as the wake fields of the acceleration modules. The CSR effects are mitigated by optimizing the Twiss parameters at each BC individually. In the next step resistive wall wake fields will be included into the simulation. To avoid unphysical micro-bunching effects due to CSR- and LSC-effects, which are driven by the larger granularity of the macro-particles, the LH is used to increase the slice energy spread and to reduce the gain of the simulated micro structures. In this article we show cases for bunch charges of 500 pC, 250 pC and 100 pC with 10 million macro particles and 20 pC with 1 million macro particles. The imprinted energy modulation of the LH is 6 keV for 500 pC, 3 keV for 250 pC, 1.5 keV for 100 pC and 2 keV for 20 pC.

For the ASTRA simulation we stick to tracking results of [12] with an RF gradient at the gun of 45 MV/m. Recent optimization of the gun for the European XFEL with increased gun gradient of 58 MV/m which is similar to the FLASH gun [13] show an improved emittance which leads to larger FEL gain at shorter wavelength [9]. In this article we limit ourself to FLASH2 to the case of a beam energy of 1350 MeV, because the high current, high beam energy case for short wavelength will have the highest demands on beam quality. Figure 2 (middle) column shows the three stage compression case while the right column the two compression stage case

is shown. It can be clearly seen the improvement of the slice emittance (factor of 3) and the uncorrelated energy spread (factor of 2) which are mainly increased by SC. Also the projected emittance is significant smaller for the three BC case (see Table 1) compared to a horizontal projected emittance of about  $5 \mu\text{m}$  in x for the two BC case. For seeded operation the peak current is about 500 A [8] where almost no dilution of the initial parameters can be observed even the projected emittance ( $\epsilon_p \sim 0.5 \mu\text{m}$  in x and  $\epsilon_p \sim 0.4 \mu\text{m}$  in y) show almost no increase (see Fig. 2 right). For the case of 250 pC the slice emittance in the head part is with  $0.7 \mu\text{m}$  slightly larger than [8] with  $0.6 \mu\text{m}$  currently is assuming. The uncorrelated energy spread is a factor of two smaller than the assumption of [8].

Table 1: Peak current  $I_p$ , normalized projected emittance  $\epsilon_p$ , normalized slice emittance  $\epsilon_s$  and slice energy spread  $\delta_s$  and of the central slice with maximum current obtained by the start-to-end simulations (S2E) are listed for different charges  $q$ . The view point of the S2E is at the entrance of the undulator in the FLASH2 beam line for a beam energy of 1.35 GeV.

| $q/\text{pC}$ | $I_p/\text{A}$ | $\epsilon_p/\mu\text{m}$ | $\epsilon_s/\mu\text{m}$ | $\delta_s/\text{eV}$ |
|---------------|----------------|--------------------------|--------------------------|----------------------|
| 500           | 2000           | 1.4                      | 0.80                     | 230                  |
| 250           | 2000           | 1.1                      | 0.60                     | 230                  |
| 100           | 2000           | 1.0                      | 0.35                     | 250                  |
| 20            | 1500           | 0.9                      | 0.35                     | 270                  |

Figure 3 shows for 500 pC, 100 pC and 20 pC the current profile, normalized slice emittance for both planes and the slice energy spread (upper row) and the corresponding longitudinal phase space is depicted in the lower row. For all four charge cases with three BCs the most important beam properties for FEL gain are gathered in Table 1. Table 2 list up the compression factors for the simulated cases at the different BCs and the total compression factor.

The power gain length and the corrected gain length [14] for 2.5 nm are about 1 m which shows that one is able to reach wavelength at the oxygen k-edge using the presented FLASH design with the introduced compression schemes.

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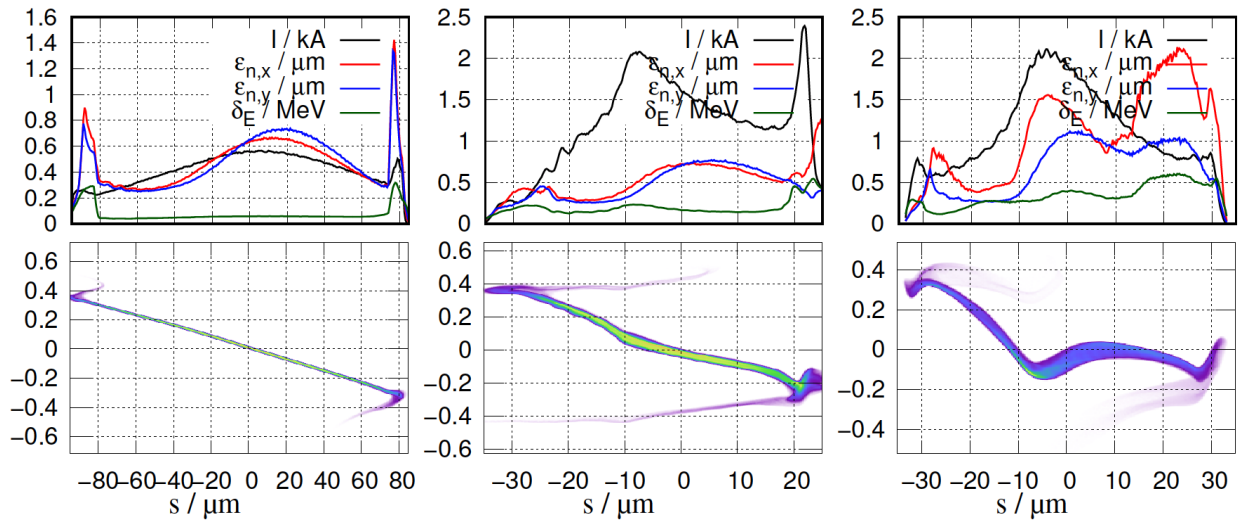


Figure 2: The upper row shows the current profile, the normalized slice emittance for both planes and the uncorrelated energy spread for 250 pC bunch charge for FLASH1 seeding (left), with (middle) and without (right) third BC in FLASH2. In the lower row the corresponding longitudinal phase spaces are depicted.

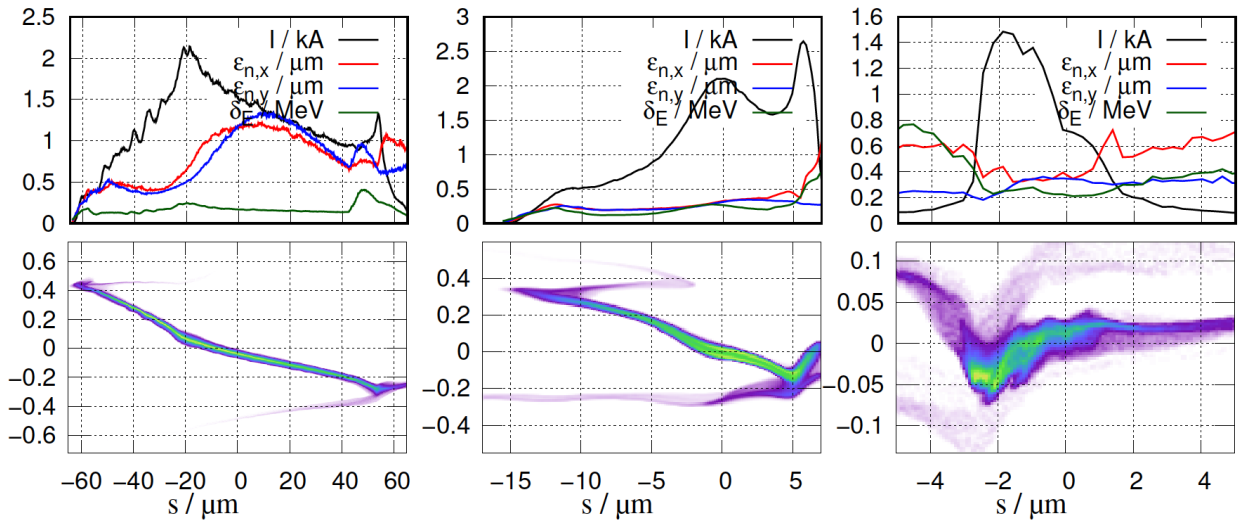


Figure 3: The upper row shows the current profile, the normalized slice emittance for both planes and the uncorrelated energy spread for 500 pC, 100 pC and 20 pC bunch charge with three BCs. In the lower row the corresponding longitudinal phase spaces are depicted.

Table 2: Compression Factor of the BCs and Total Compression Factor for the Different Considered Bunch Charges

| charge/pC | $C_1$ | $C_2$ | $C_3$ | $C_{tot}$ |
|-----------|-------|-------|-------|-----------|
| 500       | 4     | 8     | 2.5   | 80        |
| 250       | 4     | 9     | 3.5   | 250       |
| 100       | 4.5   | 10    | 5.6   | 300       |
| 20        | 10    | 10    | 6.0   | 300       |

Hence, the corrected power gain length is similar to the FEL gain length the emittance effects and energy spread effects are still small.

## CONCLUSION

We have shown compression schemes for four different charges with a peak current of around 2 kA where the high quality beam parameters from the injector are almost preserved. With the third bunch compression chicane slice energy spread and the emittance (projected and slice) will be improved significantly. This enables FLASH to reach wavelength down to oxygen K-edge at 2.3 nm. For seeded FEL operation a two stage compression is feasible to reach the aimed beam parameters. Newly optimized gun parameters will further improve the beam quality by reducing the slice emittance which is one of the most crucial parameters for the FEL gain.

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