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# THE NEW FLASH1 UNDULATOR BEAMLINE FOR THE FLASH2020+ PROJECT

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### Abstract

The 2nd stage of the FLASH2020+ project at DESY will be an upgrade of the FLASH1 beamline to enable HGHG and EEHG seeding with two modulator-chicane stages, and a radiator section with 11 APPLE-III undulators to enable FEL radiation with controllable polarization. A key feature of FLASH, namely the capability of providing several thousand FEL pulses in the extreme UV and soft X-ray must not be compromised. Downstream of the radiator the beamline houses longitudinal diagnostics, a double bend (quasi-) achromat to separate the electrons from the photons and divert the electron beamline from the photon diagnostics, a post-compressor, a THz-Undulator (requires an electron beam that is compressed more strongly than for seeding), and finally the dumpline, capable of safely aborting up to 100 kW electron beam power.

This article describes the conceptional and some technical details of the beamline with emphasis on the upstream part (modulators and radiator) designed for seeding.


## INTRODUCTION

FLASH the XUV- and soft X-ray user facility at DESY in Hamburg [1–7] is currently undergoing a substantial upgrade and refurbishment project, FLASH2020+ [8–10]. The FLASH accelerator consists of four functionally distinct sections: the common part (injector, linac), called FLASH0, which is upgraded and refurbished in the current shutdown [3, 5], the two independently operated undulator beamlines FLASH1 & FLASH2 [11, 12], and the experimental beamline FLASH3. The superconducting linac supplies long RF pulses with a flat top usable for beam operation of up to 800 µs). This flat top can be split with a transition time of typically 70 µs, so that both beamlines can be served with sub-trains of up to several hundred bunches at bunch frequencies of up to1 MHz at every RF-pulse. The RF pulse repetition frequency is 10 Hz. FLASH1 will be basically completely rebuilt in 2024/25 which is the topic of this contribution.

### *Conceptual Overview of the Beamline*

In the past both FLASH1/2 were dedicated SASE (Self-Amplified Spontaneous Emission) FELs (Free-Electron Lasers). In the future the new FLASH1 beamline, however will be optimized for high repetition rate HGHG (High Gain Harmonic Generation) and EEHG (Echo-Enabled Harmonic Generation) external seeding [9] within the FLASH2020+ project.

SASE has proven to be an extremely powerful and robust FEL mechanism, but external seeding potentially enhances the control over properties of the produced FEL radiation, i.p. the longitudinal coherence, substantially [9].

The incoming bunch is overlaid in the first undulator (modulator UM1) with the first seed laser beam (L1). Thereby an energy modulation is impregnated on the bunch PSD. Next the energy modulation from L1 and UM1 is strongly oversheared in the first magnetic chicane (**CH1**). Then the bunch is overlaid in the second undulator (modulator UM2) with the second seed laser beam (L2). Finally bunch is moderately sheared in the second magnetic chicane (**CH2**) so that its sinusoidally modulated fine structure generates bunching whose higher order Fourier harmonics will seed the FEL process in the radiator.

Downstream of the radiator the electron beam passes through a longitudinal diagnostic section before it is separated from the FEL beam, post-compressed, sent through an electromagnetic undulator for THz radiation used for highly synchronized pump-probe experiments [13] before it is finally dumped.

Here we give an overview of the FLASH1 beamline with emphasis on the FEL sections, namely the two modulator sections with their chicanes and the radiator section. The other sections of the beamline, collimation, matching, longitudinal diagnostics, horizontal separation from the FEL beam, post-compression, THz undulator and the dump beamline have been described in greater detail in [14].

## BEAMLINE DETAILS

The undulator beamline is split into several functional sections as is shown in Fig. 1

A section for diagnostic collimation and matching will be installed upstream of the modulator section immediately following the FLASH1/FLASH2 switch yard.

The modulator sections FL1MOD1/2 contain the 2.5 m long planar modulator undulators UM1 and UM2. The magnetic structure of the undulators is not yet fixed but will soon be finalized. Each modulator is surrounded by two 0.6 m long intersections (see Fig. 2 left) equipped with a beam position monitor (BPM), a quadrupole with $x/y$-mover, a screen station, 2 beam loss monitors (BLMs) and $x/y$-steering using air-coils or small ferrite coils. The modulator sections also contain the two vertical C-chicanes **CH1** and **CH2** needed for the EEHG external seeding process as briefly explained in subsection . An additional chicane **InC** (Fig. 3) is needed upstream of modulator UM1 for in-coupling of the first seed laser L1. The seed laser L2 is coupled in through **CH1** (Fig. 4) upstream UM2. The laser beams are coupled out

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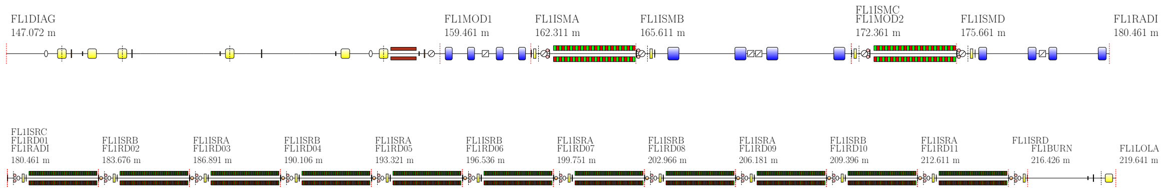

Figure 1: Schematic layout [15] of the seeded FLASH1 undulator beamline: top: FL1DIAG-FL1MOD2 ($\Delta s$ = 33.43 m), bottom: FL1RADI-FL1BURN ($\Delta s$ = 39.18 m). Each line is to scale but the two lines vary in overall length.

and diagnosed at the downstream chicanes **CH1** and **CH2** (Fig. 5).

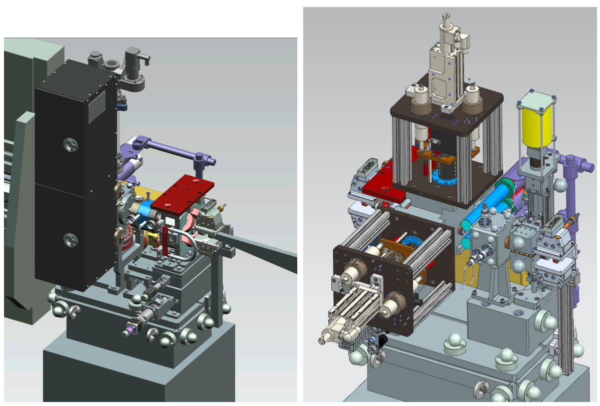

Figure 2: 3D CAD model of the intersection types used (left) with the modulator undulators, and (right) with the radiators and both both wire scanner ports equipped.

The **InC** chicane has only two operational states: active, for inserting the in-coupling mirror, and flat, for retracted mirror. The two seeding chicanes **CH1** and **CH2** need to be fully tunable during set up of the FEL Process. Because of the delicacy of the seeding process this requires almost perfect chicanes in the complete tuning range. All chicanes should guarantee an $M_{56}$-reproducibility of $1 \times 10^{-3}$, spurious dispersion < 1 mm and an orbit-closure under tuning of < 200 µm which is already technically challenging. Table 1 shows the minimum required beam offsets and the $M_{56}$ tuning ranges (for inserted and retracted in/out-coupling mirrors where applicable). The large tuning ranges are challenging because they impose large good-field regions to fully accommodate the beam for various deflection angles, and simultaneously excellent field quality inside these regions, All magnets should comply to $|\delta B dl/B dl| < 5 \cdot 10^{-4}$ inside their good-field region. The design constraints on the chicane dipoles in the FLASH1 beamline are described in detail in [14].

Table 1: Chicane specifications

| chic. | beam offset | $M_{56}$ m. in | $M_{56}$ m. out |
|---|---|---|---|
| **InC** | ≥ 7.5 mm | — | ~ 0 µm |
| **CH1** | ≥ 20.0 mm | 400 µm - 14.5 mm | 0-250 µm |
| **CH2** | ≥ 7.5 mm | 40-350 µm | 0-300 µm |

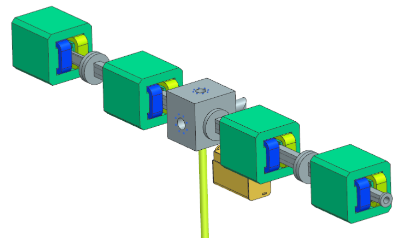

Figure 3: 3D CAD model of the in-coupling chicane **InC**. The yellow pipe is part of the in-coupling system of seed laser L1.

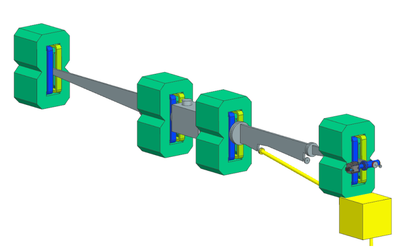

Figure 4: 3D CAD model of the over-folding (EEHG) chicane **CH1**. The yellow pipe and box are part of the in-coupling system of seed laser L2.

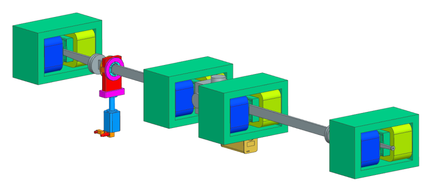

Figure 5: 3D CAD model of the bunching chicane **CH2**.

The radiator undulator section consists of eleven 2.44 m long APPLE-III-type undulator segments (see Fig. 6), surrounded and interleaved by twelve 0.6 m long intersections (see Fig. 2 right) each with a BPM, a phase shifter, a quadrupole with $x/y$-mover, a wire scanner station (either horizontal or vertical equipped[1]), 2 BLMs, and steering using air-coils or small ferrite coils.

Downstream of the 11 seed radiators space is foreseen for a 3rd harmonic afterburner which will, however, not be installed in the 2024/25 shutdown.

[1] Fig. 2 (right) shows both wire scanners equipped, which is in principle possible as a further upgrade.

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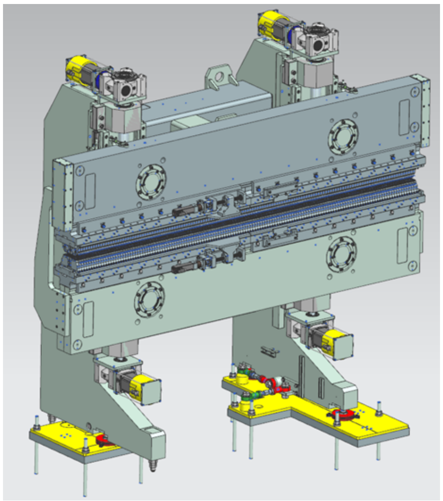

Figure 6: 3D CAD model of the APPLE-III undulator.

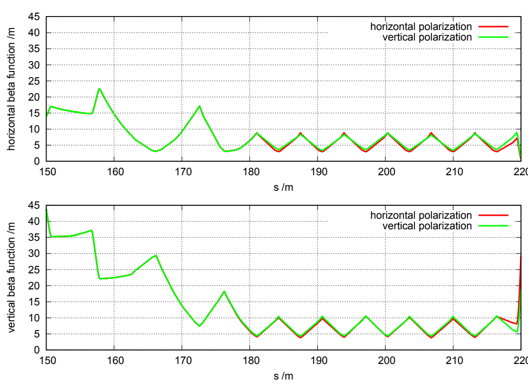


Figure 7: Optics in modulator and radiator section for different polarization settings of the radiator for a beam energy of 1350 MeV. Top: horizontal plane; bottom: vertical plane.

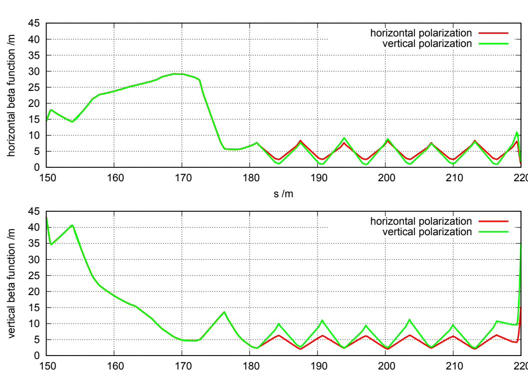


Figure 8: Optics in modulator and radiator section for different polarization settings of the radiator for a beam energy of 750 MeV. Top: horizontal plane; bottom: vertical plane.

### *Optics*

The electron optics for the FLASH1 beamline must meet many requirements to ensure good FEL performance as well as proper operability of the accelerator: (1) Efficient collimation of the electron beam. (2) Capability to measure and adapt electron optics upstream of the modulators without interfering with FLASH2 operation. (3) Electron beam size inside the modulators < 150 µm. (4) Small average beta functions in the radiator to ensure high FEL gain. (5) Optics adaption during Polarization scan should only use quadrupoles downstream of the second modulator. The above requirements must be fulfilled for the three standard energy working points: 1.35 GeV, 0.95 GeV and 0.75 GeV.

The beam optics is calculated using MAD8 [16] with Linac extensions [17, 18]. The wigglers are implemented as a matrix for planar undulator which is tilted for different polarization states.

In the septum dipole for the separation of the FLASH2 beamline, the horizontal beta function has a strong focus that needs to be matched into the FLASH1 diagnostics and collimation section. To ensure an efficient collimation, the phase advance between the two collimators should be between 60° and 120° and the beta functions at the collimators should be large. In addition, the optics must be so that the beam sizes in the modulators fulfill $\beta_{x,y}^{\mathrm{mod1,mod2}} < 30$ m assuming a normalized emittance of 1 µm. There is no additional optics matching section between the last modulator and the radiator section, not only because the beamline is lacking space, but also because we want to keep the deteriorating effects of spurious dispersion and drift-$M_{56}$ on the fine-structured phase space, prepared for seeded FEL operation as small as possible. All changes of the undulator focusing due to changes in the polarization settings and the undulator-$K$s of the radiators have to be compensated using only the last quadrupole downstream of the second modulator and the quadrupoles in the radiators section. The currently used design beam optics for the FLASH1 beamline is depicted for horizontal and vertical radiator polarization states for 1350 MeV in Fig. 7 and for 750 MeV in 8. As can be seen, the optics adaption look good but is not completely symmetric. It is obvious that the sensitivity to changes in the undulator settings is largest at small energies.

The beamline designed for FLASH1 is finished and the component design is close to finalization. We are looking forward to installing the new beamline in the 2024/25 shutdown.

## ACKNOWLEDGMENTS

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