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FLASH: THE PIONEERING XUV AND SOFT X-RAY FEL USER FACILITY

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Abstract

FLASH, the free-electron laser (FEL) at DESY (Hamburg), started user operation in summer 2005. It delivers high peak and average brilliance XUV and soft X-ray FEL radiation to photon experiments. Nowadays, FLASH has a 1.25 GeV superconducting linac, and two undulator beamlines, which are operated simultaneously. This paper provides an overview of its evolution from a test facility for superconducting accelerator technology to a full-scale FEL user facility.

INTRODUCTION

FLASH [1–6] at DESY (Hamburg, Germany) is an FEL user facility. It started user operation in summer 2005, and it was the first user facility worldwide delivering FEL radiation in XUV wavelengths to photon experiments.

Presently, FLASH consists of a photoinjector, a superconducting linac, two undulator beamlines (FLASH1 and FLASH2), and two experimental halls. The schematic layout is shown in Fig. 1. In addition, FLASH hosts a seeding experiment sFLASH [7], and a plasma wakefield acceleration experiment FLASHForward [8].

Electron bunches are generated by a photoinjector consisting of a normal conducting RF-gun with an exchangeable Cs_2Te photocathode, and three injector lasers. The linac has seven TESLA type 1.3 GHz superconducting accelerator modules, and two magnetic chicane bunch compressors. The maximum electron beam energy is 1.25 GeV. The use of superconducting RF cavities allows operation with long RF-pulses (800 µs), and thus with long electron bunch trains. FLASH1 and FLASH2 beamlines are operated simultaneously with a bunch train repetition rate of 10 Hz [9]. The separation of the bunch trains is realized by a kicker-septum system downstream of the last accelerator module.

The production of FEL radiation is based on the SASE (Self Amplified Spontaneous Emission) process. The FLASH1 undulator beamline consists of six 4.5 m long fixed gap (12 mm) undulator modules, which are the original ones and in use since 2004. FLASH2 has twelve 2.5 m long variable gap undulators. A planar electromagnetic undulator, installed downstream of the FLASH1 SASE undulators, provides, on request, THz radiation for user experiments.

The photon wavelength of FLASH1, due to fixed gap undulators, is defined by the electron beam energy. The minimum wavelength (fundamental), which FLASH1 can provide for user experiments is 4.2 nm, the maximum one slightly above 50 nm. FLASH2 with variable gap undulators provides FEL radiation at wavelengths between 4 nm and 90 nm.

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Part of the material presented here has been discussed also in previous conferences, for example in [10–14].

TESLA TEST FACILITY (TTF) LINAC

The origin of FLASH is the TESLA Test Facility (TTF) Linac [15], constructed at DESY in mid 1990's. TTF was originally dedicated to test the feasibility of high gradient superconducting accelerator technology in the framework of the TESLA linear collider project [16].

The TTF injector I [17], operated in 1996-1998, consisted of a thermionic gun, a subharmonic buncher, a capture cavity (one superconducting TESLA type 9-cell cavity), and a diagnostics section. The first electron beam was produced in April 1996. The first complete TESLA type accelerator module with eight 9-cell superconducting niobium cavities was installed into the TTF Linac in spring 1997. Successful beam tests were carried out in 1997-1998 [18].

In autumn 1998, the injector was replaced by a photoinjector (Injector II) consisting of a laser-driven RF-gun with a Cs_2Te photocathode, a capture cavity (the same one as used in Injector I), a bunch compressor, and a diagnostic section [19]. In addition, a second bunch compressor [20] and a second accelerator module [21] were installed. The bunch compressor was located between the two accelerator modules.

Moreover, the TTF Linac was used to drive the SASE free-electron laser pilot facility TTF-FEL [22]. Three fixed gap undulator modules, similar to those still in use at FLASH1, were installed in 1999. In addition, the first accelerator module was replaced by a new one. The first SASE lasing in VUV worldwide (109 nm) was achieved in February 2000 [23]. TTF-FEL was successfully operated at photon wavelengths from 80 nm to 120 nm [24, 25] to demonstrate the feasibility of SASE FELs in the VUV range for photon experiments. The operation of the TTF Linac finished in November 2002.

FEL USER FACILITY FLASH

FLASH – originally called VUV-FEL at TTF2 – was constructed in 2003-2004. The first stage consisted of a photoinjector, a superconducting linac of five TESLA type accelerator modules, two bunch compressors, and an undulator beamline of six fixed gap undulator modules. The injector and the first part of the linac were located in the former place of TTF-FEL. An extension tunnel was built to host the undulator beamline, and a new experimental hall was constructed for the photon beamlines and user experiments.

The first lasing (32 nm) was achieved in January 2005 [26]. The user operation started in summer 2005, opening new possibilities for photon science, for example diffractive imaging [27]. During 2005-2007, FLASH delivered FEL radiation in wavelengths from 13 nm to 47 nm (fundamental),

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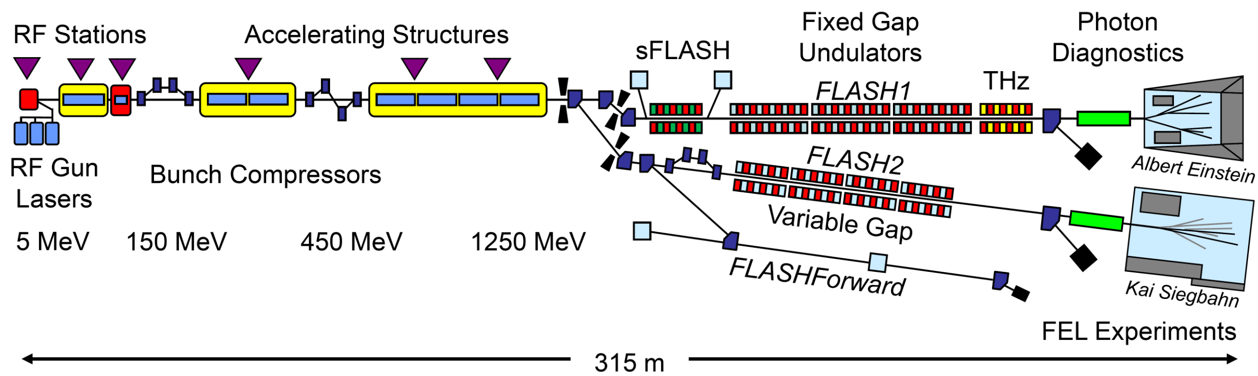

Figure 1: Schematic layout of the FLASH facility in 2019 (not to scale).

entering the water window with the third and fifth harmonics [1].

The sixth accelerator module was installed in 2007 to reach the design energy of 1 GeV. The photon wavelength range was extended to the soft X-rays with wavelengths down to 6.5 nm [28].

In 2009-2010, the last upgrade of the FLASH linac was accomplished [29]. Installation of the seventh accelerator module increased the electron beam energy up to 1.25 GeV. This allows lasing with wavelengths down to 4.1 nm [30], entering thus the water window also with fundamental wavelengths. In addition, a module with four third harmonic (3.9 GHz) superconducting RF cavities was installed to linearize the longitudinal phase space. In parallel, a seeding experiment sFLASH [31] was installed upstream of the SASE undulators.

In 2013, a second undulator beamline, located in a new building, was connected to the FLASH linac. Since then the original FLASH undulator beamline with fixed gap undulators has been called FLASH1, the new one with variable gap ones FLASH2.

FLASH2

In order to fulfill the continuously increasing demands on the beam time and on the photon beam properties, a second undulator beamline FLASH2, was constructed in 2011-2014. FLASH2 consists of an extraction beamline to connect it to the FLASH linac, an undulator beamline of twelve variable gap undulators, and a sophisticated photon diagnostics section. Photon beamlines are located in a new experimental hall [32].

The connection of FLASH2 to the FLASH linac was accomplished in 2013 within a 6 months shutdown. In winter 2013/2014, the FLASH2 beamline installation continued in parallel to the FLASH1 operation. The beam commissioning of FLASH2 started in spring 2014, and the first lasing was achieved in August 2014 [33]. Since April 2016, FLASH2 is in user operation.

The installation and instrumentation of photon beamlines has continued during the last years, allowing an increasing number of user experiments to take place at FLASH2. For example, a pump-probe laser has been available since autumn 2018. Thanks to variable gap undulators, fast wavelength scans are feasible and routinely performed by FLASH2 experiments.

FLASH2 provides also a possibility to test novel lasing schemes, like HLSS (harmonic lasing self-seeded FEL) [34] and two-color lasing [35].

A third electron beamline, located in the same building as FLASH2, hosts a plasma wakefield acceleration experiment FLASHForward [8]. Its experimental program started in 2018 [36].

PRESENT STATUS

FLASH is nowadays a full-scale of user facility with two undulator beamlines. More than 300 papers on photon science at FLASH has been published in scientific journals [37].

FLASH has two user periods per year. 60% of the available beam time is dedicated to user operation (4500 h per year), 30% to developments to improve the performance as a user facility, and 10% to general accelerator physics developments, like seeding (sFLASH) and plasma wakefield acceleration (FLASHForward). The beam time is organized with an alternating pattern of user blocks (4-5 weeks) and study blocks (2-3 weeks). Shutdown periods are scheduled twice per year: typically 4 weeks in summer and 2 weeks over Christmas.

OUTLOOK

In order to keep FLASH a state-of-the-art FEL user facility, a refurbishment and upgrade program is on-going [38].

In summer 2019, a third bunch compressor was installed at FLASH2 downstream of the extraction beamline. An installation of a transverse deflecting structure “PolariX-TDS" [39] downstream of the FLASH2 undulators is foreseen in 2020.The two oldest and weakest accelerator modules (module 2 and module 3) will be replaced in 2021 by refurbished modules with high gradient cavities. This, together with an optimization of the waveguide distribution system, will provide an energy upgrade to 1.35 GeV. In addition, several other refurbishments are on-going, concerning, for example, the injector laser system, the optical synchronization system, and electron beam diagnostics.

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As part of the DESY strategy process, an upgrade project "FLASH 2020+" has been proposed. The key aspects of the proposal are replacement of the FLASH1 undulators with variable gap ones, establishment of a high repetition rate seeding (goal 1 MHz) at FLASH1, extension of the wavelength (fundamental) range at FLASH2 down to the oxygen K-edge (2.3 nm), and exploration of possibilities for novel lasing schemes towards attosecond physics.

SUMMARY

In the last 20 years, FLASH has been a pioneer for SASE FELs. Already TTF-FEL demonstrated the feasibility of FELs in the VUV range, and in 2005 FLASH was the first facility providing SASE XUV radiation for user experiments, encouraging several other FEL user facilities, like the European XFEL, to be constructed. With several upgrades, FLASH has extended its wavelength range to soft x-rays. Since 2014, FLASH has operated simultaneously two undulator beamlines, being the first worldwide also in this aspect. We believe that with the on-going refurbishment and the planned upgrades, FLASH will stay an state-of-the-art FEL also for the coming years.

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