

# A CONCEPT FOR UPGRADE OF FLASH2 UNDULATOR LINE

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## Abstract

FLASH is the first soft X-ray FEL user facility, routinely providing brilliant photon beams for users since 2005. There are plans to upgrade both existing undulator lines of this facility, FLASH1 and FLASH2. FLASH1 will mainly operate in XUV range in seeding and SASE modes, while FLASH2 will use the standard SASE regime as well as new lasing concepts aiming at production of brilliant photon beams on the fundamental and harmonics down to 1 nm. In this paper we present a concept for FLASH2 upgrade, and discuss different advanced options.

## INTRODUCTION

FLASH is the soft X-ray FEL user facility with two undulator lines, FLASH1 and FLASH2. Upgrade plans for this facility (FLASH2020+) are under discussions [1]. FLASH1 will mainly operate in XUV range in seeding and SASE modes, while FLASH2 will use the standard SASE regime as well as new lasing concepts.

Two main goals of FLASH2 upgrade are:

- to extend photon energy range with the aim to reach Oxygen K-edge (540 eV) on the fundamental, and 1 keV with the help of special lasing schemes;
- to provide a variety of advanced options for user experiments: polarization control, two color mode of operation, attosecond option etc.

In order to reach these goals, the layout of FLASH2 FEL line, shown in Fig. 1, is proposed. Main undulator consists of two sections U1 and U2 with different undulator periods and separated by delay chicane. Undulators are of APPLE-type providing full polarization control. The choice of this technology in combination with two different undulator periods allows for a great flexibility in terms of wavelength range, operation modes, polarization control, improvement of longitudinal coherence.

## OPERATION MODES

For calculation of undulator lengths and possible photon energy ranges we use slice parameters of the electron beam simulated for the bunch charge of 100 pC (see [2]): peak current 2 kA, core slice emittance 0.4 mm\*mrad, uncorrelated energy spread 250 keV. Nominal electron energy after refurbishment of the accelerator modules will be 1.35 GeV; to increase an accessible range of photon energies, we also consider 0.75 GeV as a second standard energy. Undulator parameters of U1 and U2 are presented in Fig. 1, the undulator gap is assumed to be 8 mm. Let us discuss different operation scenarios of FLASH2 undulator line.

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## SASE Mode

Self-Amplified Spontaneous Emission (SASE) is the main operation mode that can be realized either in U1 (for longer wavelengths) or in U2 (for shorter wavelengths) or in both undulators tuned to the same wavelength (for intermediate range). Due to a combination of undulators with two different periods it becomes possible to provide broad tunability at a fixed electron energy, by an order of magnitude (to be compared with a factor of three in the present undulator of FLASH2). For two fixed electron energies, mentioned above, the tunability range in SASE mode will be from 2.3 nm (Carbon K-edge) to 60 nm.

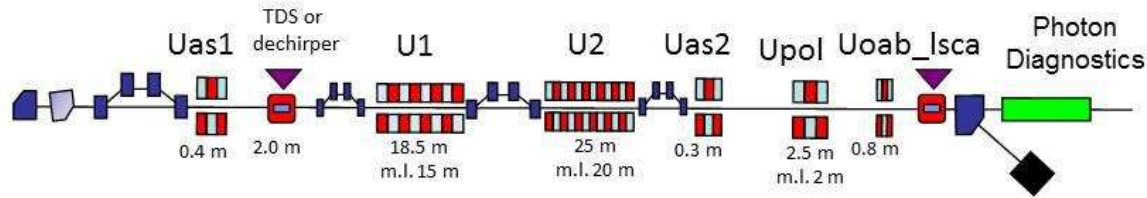
## Harmonic Lasing and HLSS FEL

Harmonic lasing in single-pass high-gain FELs [3–6] is the FEL instability at an odd harmonic of the planar undulator developing independently from lasing on the fundamental. Contrary to nonlinear harmonic generation (which is driven by the fundamental in the vicinity of saturation) harmonic lasing can provide much more intense, stable, and narrow-band FEL beam. The most attractive feature of saturated harmonic lasing is that the brilliance of a harmonic is comparable to that of the fundamental. Although known theoretically for a long time, harmonic lasing in high-gain FELs was not demonstrated experimentally until the pioneering experiments at FLASH2 in which the so-called Harmonic Lasing Self-Seeded FEL (HLSS FEL) [6, 7] worked in the range 4.5 - 15 nm [8].

For harmonic lasing operation, undulators (U1 and U2) should be tuned to linear polarization mode. Suppression of the fundamental (necessary for harmonic lasing) is achieved by two methods simultaneously: switching between the 3rd and the 5th harmonics [9, 10] and using phase shifters [5, 6]. One can also use spectral filtering method [6] by putting a filter into a delay chicane (see Fig. 1). Operation between 1 nm and 2 nm for 1.35 GeV will be possible. In case of HLSS the range would be 2-6 nm for 1.35 GeV and 6-20 nm for 0.75 GeV.

## Reverse Tapering with Harmonic Afterburner

Reverse undulator tapering is a relatively new concept [11] to be used for polarization control in X-ray FELs. This technique allows to strongly suppress radiation intensity at the exit of the main (planar) undulator while preserving strong microbunching of electron beam that produces radiation with a required polarization pattern in a variably polarized afterburner undulator. The concept is routinely used at LCLS [12] and was successfully tested at FLASH2 [13]. Moreover, the afterburner can be tuned to a harmonic of the main undulator; this option was also demonstrated at FLASH2 [14]. Polarization control at wavelengths above 2 nm can be done



U1: period 3.5 cm,  $K_{rms} = 2.55$

U2: period 2.6 cm,  $K_{rms} = 1.5$

### Main FEL modes (energies 1.35 GeV and 0.75 GeV):

- Harmonic lasing: 1 – 2 nm
- Frequency doubling or reverse taper with harmonic afterburner: 1.2 – 2.3 nm
- HLSS: 2 – 6 nm @ 1.35 GeV and 6 – 20 nm @ 0.75 GeV
- SASE: 2.3 – 18.5 nm @ 1.35 GeV and 7 – 60 nm @ 0.75 GeV
- Two colors (SASE @ 1.35 GeV): 4 – 18.5 nm (U1) and 2.3 nm – 6 nm (U2)
- Two colors (SASE @ 0.75 GeV): 11 – 60 nm (U1) and 7 nm – 20 nm (U2)

Figure 1: Proposed layout of FLASH2 FEL line with a list of lasing options and wavelength ranges. Abbreviations stand for: BC for bunch compressor, U1 and U2 for main undulators, TDS for transverse deflecting structure, Uas1 and Uas2 for undulators of attosecond option, Upol for afterburner with variable polarization, Uoab\_lsca for optical afterburner undulator.

by tuning U2 to a desirable polarization mode in SASE or HLSS regimes (in the latter case U1 should be linearly polarized). However, polarization control is especially desired in the range where L-edges of some important magnetic materials are, i.e. typically below 2 nm. In this case U2 (and maybe U1) is tuned to the second or third subharmonic of a desired wavelength. Reverse taper is applied there in order to suppress radiation from this undulator: the fundamental (for any polarization of U2) as well as harmonics (when U2 is in linear polarization mode). However, fully microbunched electron beam contains harmonics of density and can produce powerful radiation in the afterburner Upol, tuned to the resonance with a corresponding (2nd or 3rd) harmonic. The afterburner will be built with the help of the APPLE technology but with a smaller period than U2. It will consist of two sections separated by a phase shifter. Such a configuration is sufficiently flexible and would allow to produce a desirable polarization pattern.

### Frequency Doubler

The frequency doubler (more generally, frequency multiplier) operates as follows [15, 16]. Undulator is divided into two parts. The second part is tuned to the double frequency of the first part. Amplification process in the first undulator part is stopped at the onset of the nonlinear regime, such that higher harmonic bunching in the electron beam density becomes pronouncing, but the beam quality is not disturbed significantly. Modulated electron beam enters the second part of the undulator and generates radiation at the 2nd harmonic. The scheme was tested at LCLS [17] and

at FLASH2 [18]. In the latter case the shortest wavelength at FLASH, namely 3.1 nm (this is Nitrogen K-edge) was achieved [18].

The most efficient use of frequency doubler assumes installation of a chicane between two parts of the undulator (or, two different undulators) [16]. This option can be used in the setup shown on Fig. 1 with the compact chicane behind U2. The aim is to generate intense soft X-ray beam below 2.3 nm.

### Two-color Lasing

Two colors can be produced for different purposes and in different ways. One purpose would be to serve two users at a time. In this case we can use the principle of betatron switcher [19] kicking some bunches in the pulse train with the help of the extraction kicker. Betatron phase advance can be organized in a way that these bunches oscillate in U1 and do not lase there but after orbit correction with a static steerer they go straight in U2 and lase to saturation. Non-kicked bunches first go straight in U1 producing SASE there but then they are kicked by the same steerer and do not lase in U2. If kick is done in a vertical plane, one can organize an orbit kink between the undulators horizontally so that the X-ray beams are spatially separated. Another application of two-color lasing is pump-probe experiments when both colors go to the same user. In this case instead of extraction kicker one should use a device providing kicks on a femtosecond time scale. This can be either a transverse deflection cavity as suggested in [19] or a dechirper [20], see Fig. 1. The latter method is successfully used at LCLS [20].

To provide a controllable time delay between two X-ray pulses of different colors, one can use a delay chicane shown in Fig. 1. Wavelength ranges for two-color operation can also be found in Fig. 1. Note that two-color lasing with alternation of tunes of undulator segments was recently demonstrated at FLASH2. This option can also be used after the proposed upgrade but then for pump-probe experiments users would need to use a split-and-delay line. More comfortable for users would be the scheme with the chicane, described above.

### Optical Afterburner (OAB)

This concept was proposed in [21], it uses features of SASE FEL process. Namely, energy modulations occur not only on the scale of the resonant wavelength, but also on the scale of coherence length. If a chicane with a sufficient R56 strength (longitudinal dispersion) is installed after the undulator, FEL induced energy loss modulations can be converted into the density modulations on the same scale (modulations are broadband, the central wavelength can be shifted by changing R56). Then the modulated beam radiates in a dedicated afterburner undulator, the bandwidth of the radiation scales as inverse number of periods. Two possible applications of this effect were identified in [21]: production of the second (long wavelength) color for jitter-free pump-probe experiments and measurements of FEL pulse duration (in fact, we obtain an optical replica of X-ray pulse that can be measured with standard optical methods). The concept was successfully tested at FLASH1 [22] and was used in the pulse length measurement campaign [23]. For the considered parameters and proposed layout of FLASH2, the radiation can be produced in visible and near infrared ranges with the help of the chicane after U2 and the undulator  $U_{oab\_lsc}$ . This undulator consists of five periods with a period length about 15 cm, the parameters can be further optimized.

### Longitudinal Space Charge Amplifier (LSCA)

The LSCA concept is proposed in [24] and is based on the predicted and observed LSC instability in linacs with bunch compressors. LSCA consists of a sequence of focusing channels and chicanes with a radiator undulator at the end. Experiments in visible range were carried out in SLAC [25] and recently at FLASH [26]. However, operation of LSCA in VUV range is still to be demonstrated. The proposed layout of FLASH2, shown in Fig. 1, would allow to test and to use VUV LSCA without installation of any dedicated hardware. Three chicanes are meant to be designed for other purposes, and the undulator  $U_{oab\_lsc}$  can be used in two schemes, OAB (see above) and LSCA. The expected wavelengths span from a few tens nm to a visible range, bandwidth would be in the range of tens of per cent. Pulses with a large bandwidth can be interesting for some experiments, they can be produced together with FEL pulses (by the same electron bunch).

## FEMTO- AND ATTOSECOND PULSES

Short FEL pulses down to  $\approx 1$  fs duration can be produced directly due to a short electron bunch and "single-spike lasing" that is routinely used at FLASH presently to operate the machine on 10 fs scale [27]. The installation of a new bunch compressor right in front of the undulator line and operation at 1.35 GeV will make it possible to produce very short high-quality bunches in low-charge mode (about 10 pC). Another option would be an essentially nonlinear compression of bunches with higher charge in the same way as it was done in early years of FLASH operation [28], namely producing a bunch with a short lasing part and a long low-current tail.

Another option for  $\approx 1$  fs regime would be to use a standard "long" electron bunch and to apply one of the schemes relying on a laser manipulation of electron beam, namely "chirp-taper" scheme [29]. Electron beam is modulated by a two-cycle laser pulse in the two-period undulator Uas1 (Fig. 1) such that there is a slice with the strongest energy chirp. A linear undulator taper is used to compensate FEL gain degradation within this slice [29]. The rest of the bunch has no strong chirp and suffers from the uncompensated taper. In case of hard X-rays the scheme works with Ti:Sa laser (wavelength 800 nm), and the duration of X-ray pulses can be about 200 as [29]. For soft X-ray regime a longer wavelength laser (2 - 3 micrometers) is needed [30] to better match the lasing area and FEL coherence length; the pulse duration is about 1 fs or longer. In order to further reduce pulse duration one can make use of the fact that the X-ray pulse is chirped. Thus, it can be either cut in frequency and time domain by a monochromator or compressed in a grating compressor. Note also that an alternative to the chirp-taper scheme can be so called eSASE option [31] with generation of a short high-current spike in the chicane placed in front of U1.

We can also consider a more advanced attosecond option, based on the longitudinal space charge amplifier (LSCA) [32]. The simulations show that soft X-ray pulses with a duration below 100 as can be produced. However, an essential advance in experimental demonstration of capabilities of LSCA concept is required to make a decision on the implementation of the LSCA-based attosecond scheme at FLASH2. In this case some modifications of the layout shown in Fig. 1 will be needed.

We also proposed an FEL based scheme for FLASH2 upgrade [1] which promises to deliver soft X-ray pulses on 100 as time scale. Short undulators Uas1 and Uas2 will be used in this scheme.

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