FIRST LASING OF AN HGHG SEEDED FEL AT FLASH

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Abstract

The free-electron laser facility FLASH at DESY operates in SASE mode with MHz bunch trains of high-intensity extreme ultraviolet and soft X-ray FEL pulses. A seeded beamline which is designed to be operated parasitically to the main SASE beamline has been used to test different external FEL seeding methods. First lasing at the 7th harmonic of a 266 nm seed laser using high-gain harmonic generation has been demonstrated.

INTRODUCTION

The seeding section at the Free-electron Laser in Hamburg (FLASH) facility was named sFLASH and designed to be operated in parallel with the FLASH1 and FLASH2 SASE sections [1] (Fig. 1). These three beamlines have been operated simultaneously in SASE mode with a peak current of 1.3 kA and wavelengths of 13.7 nm in FLASH1, 20 nm in FLASH2, and 38.1 nm in sFLASH. Operation of the sFLASH section in seeded-mode can potentially be done parasitically with <kA peak currents and improved quadrupole alignment.

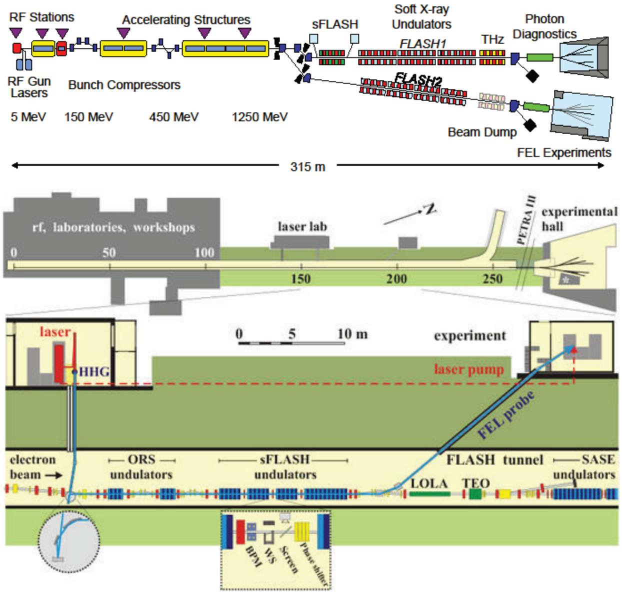

Figure 1: Layout of the FLASH facility and the sFLASH seeding section. The sFLASH section is designed to be operated in parallel with SASE generation in FLASH1 and FLASH2. It is followed by the RF deflector LOLA which makes longitudinal phase space distribution measurements. The seed laser is split so that part can be sent to the FEL user station for pump-probe experiments.

Seeding takes place when the electron bunch interacts with a laser pulse within an undulator magnet known as a modulator. The resulting sinusoidal energy modulation is transformed into a density modulation via longitudinal dispersion (Fig. 2). For a seeded FEL using the High-Gain Harmonic Generation (HGHG) scheme, microbunch trains with the periodicity of the seed laser wavelength will radiate at a harmonic of the microbunch repetition rate when they are sent through an FEL radiator tuned to that harmonic; shorter microbunches will have higher harmonic content [2,3].

For the first time at FLASH, lasing at the 7th harmonic of a 266 nm seed using high-gain harmonic generation has been demonstrated. The 266 nm seed pulses were generated from 800-nm Ti:sapphire light by using a frequency tripler made up of BBO crystals and crystalline quartz waveplates [4]. The mean pulse energy was (12 ± 12) μJ, the maximum pulse energy was 75 μJ, and the estimated gain length was ~0.9 m. The bandwidth was 0.2 nm (FWHM) with $\Delta\lambda/\lambda = 5.2\times10^{-3}$. Future efforts will be concentrated on improving the stability of the seeded beam, parasitic operation, and progress towards Echo-Enabled Harmonic Generation (EEHG) [5,6] seeding.

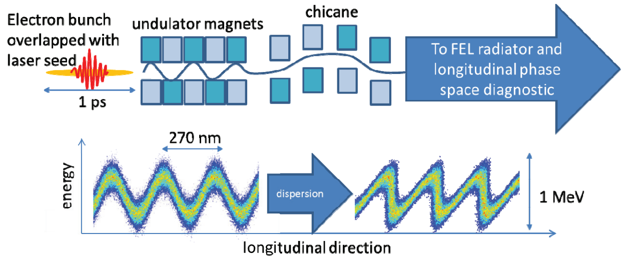

Figure 2: The HGHG experiment uses electron bunches with a peak current between 0.5 and 1 kA together with a 266 nm seed pulse, a 5 period undulator, and a chicane with ~100 μm of longitudinal dispersion.

MILESTONES

The HGHG seeding experiment was conceptualized in 2011 [5,7] and a dedicated seed injection setup was partially commissioned in 2012 [8], but filamentation of

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the 266 nm seed stopped the project's progress. It was found that the filamentation problem was removed through the use of a thinner waveplate and timeplate in the frequency tripler. In 2013, a new effort [9] aimed to increase the flexibility of the experiment from single wavelength (266 nm) to multiwavelength (266, 400, and 800 nm) operation, but in commissioning attempts in 2014, problems with the new filters and multiwavelength dielectric mirrors installed in the injection line forced their replacement with the original hardware before seeding could be achieved in 2015.

The filters in the injection line steered the beam so that the seed position in the electron beamline was significantly different with the filters in or out, preventing spatial overlap with the electrons. The effect was not easily detectable with the diagnostics 6 meters upstream in the injection line.

The use of the multi-wavelength dielectric mirrors caused all three wavelengths emerging from the tripler: 800 nm, 400 nm, and 266 nm to be sent into the modulator and it appeared that when the modulator was tuned to be resonant at 266 nm, only 800 nm and 400 nm modulation was observed in measurements of the longitudinal phase space distribution of the seeded beam, making it impossible to identify any modulation at 266 nm, despite the adequate temporal separation of the 3 pulses.

An explanation for this observation of sub-harmonic modulation which is consistent with simulations is that an intensity gradient of the seed in the modulator could have been produced if the electron beam trajectory was at an angle with respect to the laser trajectory. Systematic scans of the sensitivity of the relative magnitude of the modulations to transverse overlap in the modulator were not, however, possible. An alternative possibility is that one of the electromagnetic modulator's 5 periods + 2 half periods was damaged, although this was not detected through in-tunnel measurements with a Hall probe or current meter.

The multi-wavelength dielectric mirrors also likely caused the polarization-dependent longitudinal splitting of the seed pulse which was observed with the longitudinal phase space distribution measurements of the 800 nm seeded electron bunch (Fig. 3). When the polarization of the 800 nm seed was in a mixed state as it propagated through the dielectric coatings on the mirrors, the *s* polarized light and *p* polarized light would travel different distances, leading to longitudinal splitting of the 50 fs (FWHM) pulses. After this splitting, the polarization was rotated again at a crystalline quartz window which would make a double pulse with the correct polarization for the modulator. With these mirrors, this effect would also likely be present at 400 nm and 266 nm.

In the original setup from 2011 [10], the waveplate locations and single-wavelength, 266 nm dielectric coatings were thinner and selected to avoid this problem. In 2014, the injection optics were returned to the 2011 design and a clear 266 nm modulation was observed with the longitudinal phase space diagnostic, however evidence of bunching in the radiator was not observed. The final barrier to FEL saturation was quadrupole alignment.

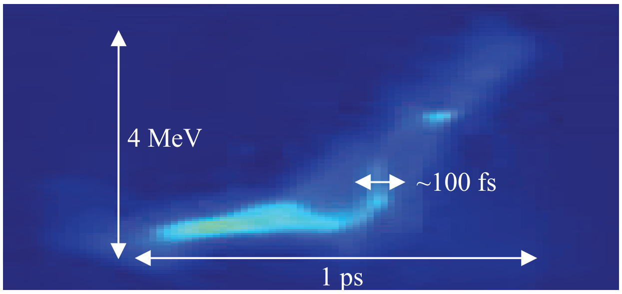

Figure 3: An RF deflecting cavity and a magnetic spectrometer are used to perform a measurement of the longitudinal phase space distribution of the 700 MeV, 0.3 kA seeded electron beam after the FEL radiator. The 800 nm, 50 fs (FWHM) seed imprinted on the electron bunch is split longitudinally, possibly via different path lengths traveled by *s* and *p* polarized light in multi-wavelength dielectric mirrors in the injection line. The 50 fs (FWHM) seed pulse length is measured prior to the entrance to the injection line.

As described in [7], the experiment would benefit from the addition of movers to the quadrupoles in the modulator section. Centering the quads with respect to the seed laser defined trajectory would ensure that the microbunches are not longitudinally smeared out in the radiator. In practice, turning off the most misaligned quadrupoles made the trajectory straight enough that FEL saturation was achieved in 2015 without the installation of movers on the quads. The seed laser and screens around the modulator and radiator segments were useful in establishing this trajectory.

FIRST LASING

As observed at Fermi in Trieste [3], the linearity of the electron bunch energy spread over the seeded region is important in establishing a narrow, stable FEL spectrum. The microbunching instability can also increase the slice energy spread of the electrons and degrade the FEL performance. Direct studies of these issues have not yet been conducted, however, it was observed in longitudinal phase space distribution measurements conducted with an RF deflector and a spectrometer that the linear energy chirp shown in Fig. 4 produced the narrowest FEL spectrum (Fig. 5), while a distribution showing a nonlinear chirp with significant microbunching instability produced a wider, more distorted spectrum [11].

The mean FEL pulse energy was (12±12) μJ, the maximum pulse energy was 75 μJ, and the estimated gain length was ~0.9 m. The background SASE signal was (2.6 ± 0.2) nJ. The bandwidth was 0.2 nm (FWHM) with $\Delta\lambda/\lambda = 5.2 \cdot 10^{-3}$. The jitter in the signal strength was dominated by pointing jitter of the seed.

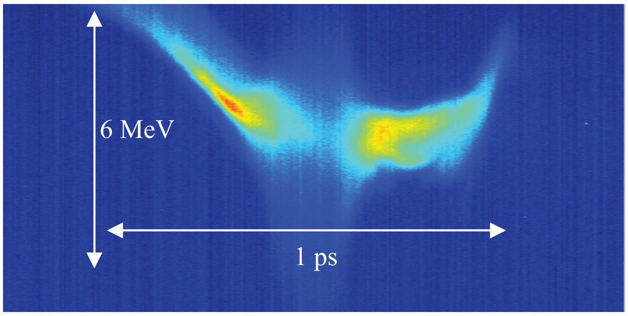

Figure 4: An RF deflecting cavity and a magnetic spectrometer are used to perform a measurement of the longitudinal phase space distribution of the 700 MeV, 0.5 kA, 266 nm seeded electron beam after the FEL radiator. The measurement is affected by the FEL process and the transverse beam size, as well as collective effects on the microbunches (see [12,13]).

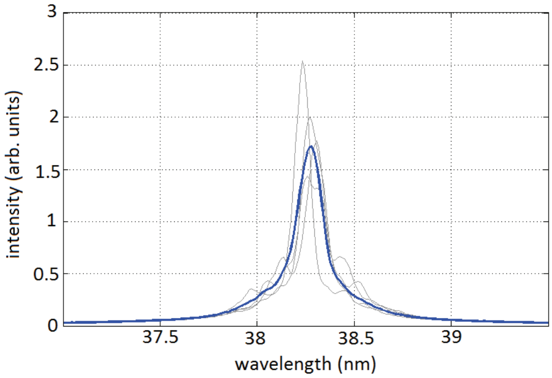

Figure 5: The FEL light is extracted from the beamline and reflected into a spectrometer. The blue curve is the average and the grey curves are individual shots.

The pointing jitter of the seed laser was initially the primary driver of variations in the intensity of the seeded FEL light, leading to 100% fluctuations as the transverse overlap changed by up to the full beam-diameter from shot to shot. After turning off un-necessary vacuum pumps and putting the IR light on the laser table into pipes in order to shield it from air currents, the pointing jitter improved by more than a factor of two.

FUTURE GOALS

After studying the performance of HGHG, the next step is to use the existing hardware to attempt an EEHG experiment (Fig. 6). Small changes to the hardware can provide adequate laser conditions for seeding at a wavelength of 266 nm in the first modulator and at 800 nm in the second modulator.

It was initially planned to use 266 nm in both modulators by splitting the 10 GW output of a single tripler [9], but tripler performance under those conditions has proven to be unstable. By reducing the bandwidth and lengthening the pulse sent into the tripler from 30 fs to 50 fs, better stability has been achieved, but at a cost to the desired peak power.

The goal is to attempt EEHG at the shortest wavelengths yet demonstrated and to determine the limitations of our ability to transport the fine EEHG microstructures into the radiator. With the 266/800 nm combination, we anticipate a minimum wavelength of 30 nm. By splitting the 800 nm pulses, to make the experiment with a combination of 266 nm and 400 nm, a minimum wavelength of 20 nm is expected (Fig. 7). A final upgrade with 266 nm in both modulators is expected to produce a minimum wavelength of 10 nm in the seeded radiators and to have the capability to be used to directly seed the downstream SASE undulators at a wavelength of 4-5 nm in a sort of directly seeded cascade [7].

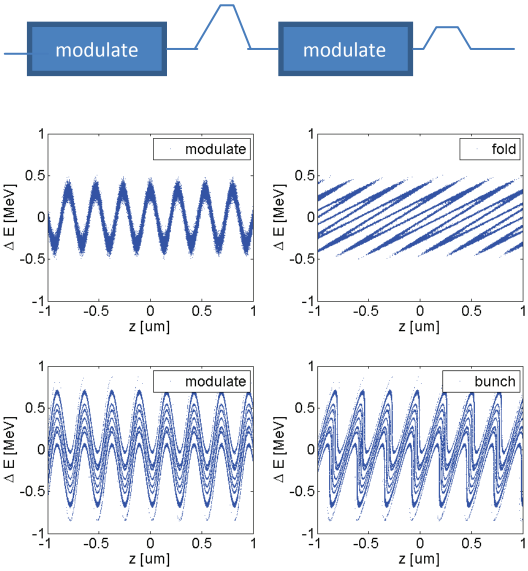

Figure 6: Echo-enabled harmonic generation (EEHG) uses two modulation stages in order to seed shorter wavelengths. It has not yet been demonstrated below 100 nm. A scheme using 266 nm in both stages is plotted.

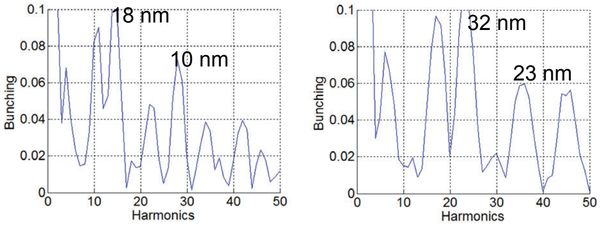

Figure 7: Harmonic content of 266/266 nm EEHG (left) and 266/800 nm EEHG (right). The sensitivity to electron beam energy jitter was taken into account in the selection of the operation points.

A key challenge of commissioning the seeding experiment at FLASH is related to the difficulty of working parasitically at an active user facility. Since demands for user beam time are high, access to the machine is limited. However, the potential to expand the user capabilities of the facility with an additional seeded beamline has kept the effort alive.

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CONCLUSION

Commissioning of the HGHG seeding experiment at FLASH was started in 2012 and achieved success in 2015. The maximum pulse energy was 75 µJ and bandwidth was 0.2 nm (FWHM). Future goals include improving the stability of the HGHG seeded beam, testing the performance limitations, and working towards EEHG.

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