PROGRESS TOWARDS HGHG AND EEHG SEEDING AT FLASH

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Abstract

Using the undulators and chicanes developed for an Optical Replica Synthesizer (ORS) experiment together with the sFLASH 800 nm seed laser, undulators and diagnostics, a High Gain Harmonic Generation (HGHG) seeding experiment will be conducted at the Free-Electron LASer in Hamburg (FLASH) starting in September 2012. For this experiment, a 30 mJ 160 fs FWHM 800 nm laser pulse has been transported with a new, evacuated laser transport line. On an in-vacuum optical breadboard, the laser frequency was tripled through second and third harmonic generation in beta-BBO crystals. Longitudinal and transverse overlap with the electron beam has been achieved through streak camera and Ce-YAG screen diagnostics. Once the HGHG seeding has been established, a shutdown period in early 2013 will be used to add a UV-TG FROG diagnostic for seed laser characterization. An additional alpha BBO crystal will be installed in order to split the 270 nm beam longitudinally into two pulses with orthogonal polarization states corresponding to the orthogonal orientations of the ORS undulators, setting the stage for Echo-Enabled Harmonic Generation (EEHG) seeding experiments in 2013.

INTRODUCTION

High Gain Harmonic Generation (HGHG) seeding has been successfully demonstrated by several facilities [1-3] and has been used to deliver fully coherent FEL pulses with wavelengths ranging from 20-50 nm to users at the ELLETRA facility in Trieste since 2010 [4]. At FLASH, a new 270 nm laser transport line has recently been added to the existing sFLASH seeding infrastructure [5-9] in order enable similar HGHG seeding experiments in the sFLASH section.

First overlap between seed and electron bunch was achieved in June 2012 and first seeding is expected during shifts scheduled for September-November 2012. After learning from the sensitivity of HGHG seeding to laser and chicane parameters, we plan to upgrade the laser setup during a shutdown in early 2013 to begin Echo-Enabled Harmonic Generation (EEHG) seeding experiments at 14 nm. This constitutes an attempt at external seeding in a wavelength range which is shorter than what has been achieved by any facility to date.

EEHG is a technique which was proposed in 2008 [10, 11] that calls for the co-propagation of an electron bunch and laser pulse through a series of three undulators and two chicanes (Fig. 1). Through interaction with a seed laser, the electron beam develops an energy modulation in the first undulator which is then over-compressed in the first chicane. The electron bunch is then modulated again in the second undulator by another laser pulse and compressed in the second chicane, resulting in vertical stripes of charge in longitudinal phase space with a periodicity of a mixture of seed laser harmonics.

EEHG schemes have been proposed for several seeded FELs [12-14] and two experiments have been able to generate low harmonics of the seed laser wavelength [15,16]. These EEHG schemes all call for a large R_{56} (1-10 mm) in the first chicane. With the first Optical Replica Synthesizer (ORS) chicane at FLASH [17], one can achieve a maximum R_{56} of 0.7 mm and while this is somewhat small compared to other proposed schemes [12-14], the amount of laser power available in this section is large, enabling EEHG for seeding wavelengths between 10 and 30 nm.

If seeding at 14 nm is successful, using the beam to seed at the 3rd harmonic in the subsequent SASE undulator section would be a natural next step. This would potentially produce fully coherent 4.7 nm radiation for users (Fig. 1).

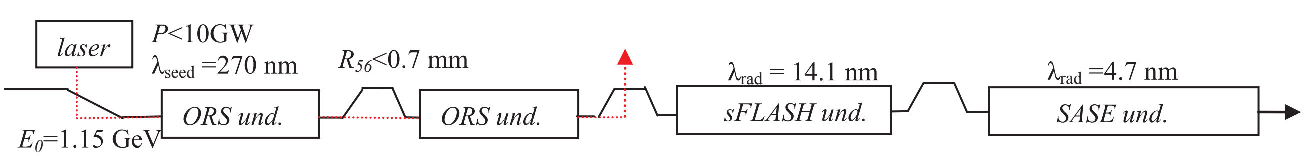

Figure 1: The FLASH I ORS section is located directly prior to the sFLASH undulators. The sFLASH undulators are followed by a small chicane and the "SASE" undulators. Using EEHG to seed the sFLASH undulator section with 14 nm could enable an HGHG scheme at 1.15 GeV to seed the SASE undulator section with 4.7 nm. The laser, diagnostics, chicanes, and undulators are already commissioned.

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Existing sFLASH [17] diagnostics, like YAG/OTR screens, spectrometers, streak camera, have already been commissioned and are all ideally suited for use as HGHG and EEHG diagnostics. The transverse deflecting cavity, LOLA [18], will be instrumental in diagnosing seed overlap and slice energy spread.

UNCORRELATED ENERGY SPREAD

The principle advantage of EEHG over HGHG lies in its tolerance of the uncorrelated energy spread of the electron beam. By stretching out and folding over the microbunches, the effective slice energy spread of a microbunch is reduced. This is especially apparent when one plots the bunching factors which can be achieved at various harmonics for HGHG and EEHG with different uncorrelated energy spreads (Fig. 2). At FLASH, 250 keV is a reasonable expectation for the uncorrelated energy spread, but it can be better under some circumstances [18]. Based on this, we can make lower limits on the achievable wavelengths for HGHG and EEHG of 20 nm and 10 nm respectively.

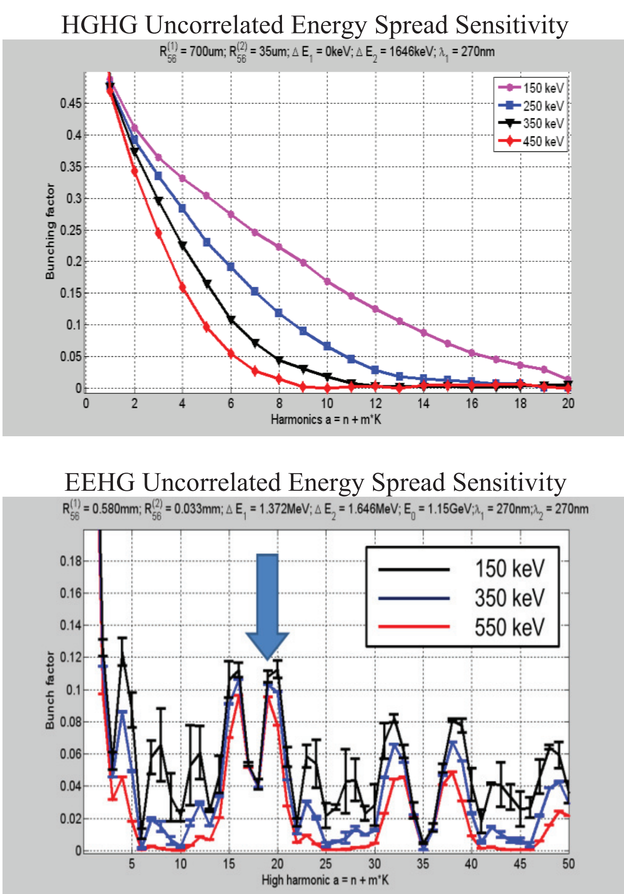

Figure 2: The sensitivity of HGHG and EEHG to rms uncorrelated energy spread with the bunching factor plotted as a function of the harmonic number. Bunching factors which are greater than 0.05-0.1 are typically sufficient for seeding. The arrow indicates the operation point for the 14 nm EEHG seeding scheme.

SEED PROPERTIES

The sFLASH seed laser system produces 800 nm light with a pulse energy which can be adjusted up to 30 mJ and a pulse length which can be adjusted between 30 fs and a picosecond. The laser and a pulse compressor are followed by a Galilean telescope on an optical table in a laser lab adjacent to the tunnel. After the telescope, the 16 mm (FWHM) diameter beam is periscoped down through a hole in the floor into a pit. The pit is connected to the accelerator tunnel by a 7 meter long tube. The first of the ORS undulators is 5 meters after the injection point in the tunnel (Fig. 3).

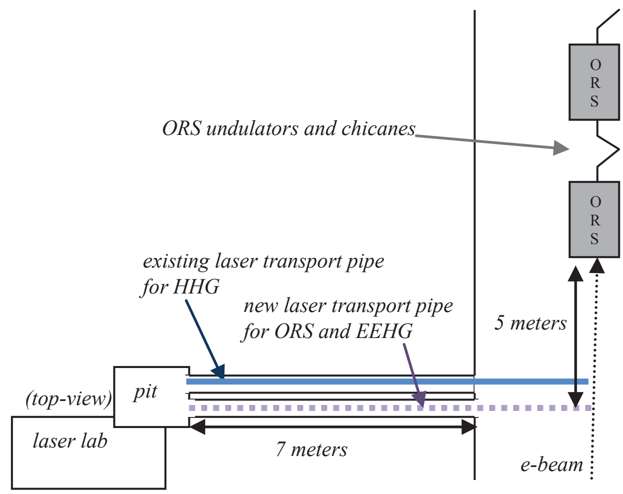

Figure 3: Location of new laser transport line with respect to the accelerator tunnel, laser table and first ORS undulator.

The new, 10^{-6} mbar evacuated laser transport pipe starts in the pit with a 5 mm thick fused-silica window followed by 8 meters of evacuated DN50 ISO-KF pipe. The laser beam then enters the first of two 70x30x30 cm evacuated boxes installed in the accelerator tunnel. These boxes are followed by another segment of pipe and two flange mounted steering mirrors, the last of which reflects the laser beam onto the electron beam axis.

The evacuated boxes contain optical breadboards on which a frequency tripler, a polarization controller, a Galileo telescope, and two motorized steering mirrors can be mounted. Two more motorized steering mirrors are mounted in vacuum flanges following the boxes. A window directly after the last box marks the transition between the high vacuum (10^{-6} mbar) of the laser transport line and the ultra-high vacuum (10^{-9} mbar) of the accelerator. The layout of these components is depicted in Fig. 4.

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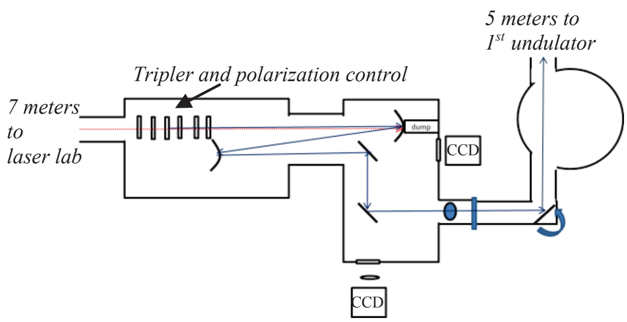

Figure 4: Layout of optics in the accelerator tunnel. Frequency tripler and polarization control optics are followed by a Galilean telescope and four motorized steering mirrors. A window sits between the last two mirrors.

The optics in these boxes were assembled in a clean room before they were installed in the tunnel. In the tunnel, it is possible to access the optics by opening one of the panels on the box. Opening and closing the boxes and pumping back down to 10^{-6} takes a matter of a few hours. Full clean room protocols have not been followed in the tunnel, and, so far, in six months, we have not yet identified problems with dirty optics. It is, however, an item of concern.

The beam size must be made as large as possible when it travels through windows and air. This is due to the non-linear phase shift in refractive materials. Two Galilean telescopes, one in the laser lab and one in the tunnel, can be used to first enlarge the beam and then create a beam waist between the two first undulators. In the design shown in Fig. 4, a 760 µm (FWHM) beam waist in the undulator section would be positioned between the two undulators, so that a 170 fs (FWHM) beam with 1.6 mJ of pulse energy can have a maximum intensity of $\sim 1 \cdot 10^{12}$ W/cm^2 in each undulator and a non-linear phase shift at the 1 mm thick crystalline quartz window equal to 0.35, a value which is well enough below one that pulse distortions should not be a problem.

During commissioning of this design, we found that the tripler crystals which were selected and simulated were too thin to achieve our target pulse energy for a 170 fs (FWHM) pulse. Instead, the tripling efficiency was maximized for 30 fs long pulses, leaving us with an appropriate peak power, but a pulse which is shorter than we would like. We will install thicker crystals next month and hope to reach our design target with them.

For initial experiments in 2012, we have also found that without the additional telescope in the tunnel, we still have adequate control over a 500 um (FWHM) waist in the ORS section. The waist can be adjusted by tuning the 800 nm telescope in the laser lab. While changing the beam size at the tripler has an impact on the tripling efficiency, we have found this impact to be slight and are very pleased at the reduction in complexity that the single telescope solution affords. When we need more control through, for example, wavefront tuning with deformable mirrors, we will add the second telescope to the setup.

Polarization control and synchronization will be accomplished through a half-waveplate and a birefringent crystal which will split the pulse longitudinally into pulses with orthogonal polarizations corresponding to the orthogonal orientations of the undulators (Fig. 5). 25 fs synchronization between seed and electron beam will be accessible through the optical synchronization system [19].

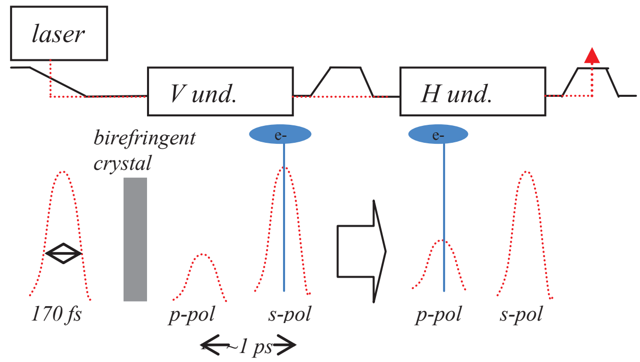

Figure 5: Generating a delay between *s* and *p* polarization so that the pulse can be used to seed in both undulators. The undulator labeled *H und.* produces horizontal oscillations and *V und.* produces vertical oscillations.

WAVEFRONT CONTROL

The wavefront quality of the laser becomes important as one attempts to reach shorter wavelengths with HGHG or EEHG [7]. It is especially of concern for wavelengths below 20 nm, as the best wavefront measurements do not have a resolution below 3 nm. Although it is important to point out that for HGHG cascades where saturation is reached in the first stage, the wavefront would be effectively cleaned up through the amplification process.

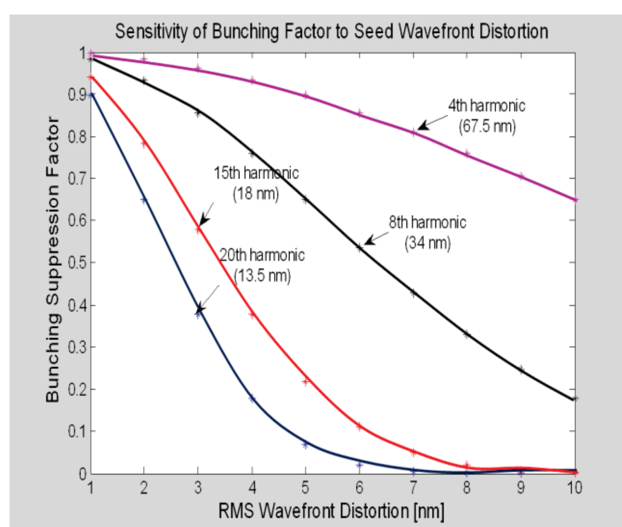

Figure 6: Sensitivity of bunching factor to seed wavefront distortion. Distortions below 3 nm cannot be directly measured.

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In order to reach the shortest wavelengths, it is anticipated that an adaptive optics package involving two deformable mirrors and measurements of the wavefront will be required in order to modulate the energy of a sufficient transverse portion of the electron bunch with sufficient quality. The quality of the laser wavefronts will directly translate to the quality of the microbunches.

A deformable mirror would be beneficial prior to the tripler (out-of-vacuum) and after the tripler (in-vacuum). The first mirror would be used to optimize tripling efficiency and the second would be used to optimize the focus in the e-beamline. One can tune such a deformable mirror with learning algorithms which use either screen images or direct measurements of the wavefront. This work is planned to start in early 2013.

CONCLUSION

EEHG is a new technique and the ORS-sFLASH section is suitable for HGHG experiments with wavelengths down to 20 nm and EEHG experiments generating wavelengths ranging down to 10 nm. Using the 14 nm EEHG beam in an HGHG cascade into the SASE undulators could enable seeding at even shorter wavelengths. The already commissioned sFLASH hardware is ideally suited for use with a HGHG and EEHG experiments. A new laser transport line has been commissioned to deliver 270 nm seed pulses to the sFLASH section. Transverse and longitudinal overlap was achieved in June 2012, first HGHG seeding is expected in Sept 2012. Remote control of the laser steering, power, and polarization has been commissioned. Wavefront tuning with adaptive optics and seed characterization with a TG FROG will be started in early 2013 in parallel with an upgrade from HGHG to EEHG experiments.

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