PROPOSED EXTENSION TO THE 250 MEV INJECTOR BEAMLINE AT PSI FOR TESTING SEEDING OPTIONS AT SWISSFEL

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Abstract

The Paul Scherrer Institute is proposing an X-ray Free-electron Laser facility operating in the wavelength range of 0.1 to 7 nm. The overall design aims for a compact layout and relies on a low emittance electron beam and short period undulator. As an initial step, a 250 MeV injector is currently under construction to demonstrate a high brightness electron beam sufficient for operating SwissFEL. An extension of the 250 MeV injector is under consideration to test additional key components for SwissFEL. Those are prototypes of the in-vacuum undulator modules as well as the proof-of-principle demonstration of echo-enabled harmonic generation as a possible seeding option for SwissFEL at 1 nm. The combination of seeding and prototype undulator module allows for saturation of the FEL at 50 nm and first experiments with FEL radiation at the PSI.

INTRODUCTION

The concept of echo-enabled harmonic generation (EE-HG) [1] has the potential to surpass the High Harmonic Generation (HHG) [2] as a seeding source for soft X-ray Free Electron Lasers [3]. HHG has shown sufficient pulse energy down to a wavelength of 10 nm [4], however the drop in the HHG efficiency at shorter wavelength is exponential, while the intrinsic shot noise power of the FEL increases with beam energy [5]. Progress towards shorter wavelength with sufficient power has been slow and it cannot be foreseen that HHG can provide a sufficient seeding source for SwissFEL [6]. In contrast, the EE-HG has no obvious limitation, which prevents wavelength at 5 nm (or even lower). The seed of the EE-HG can easily cover the entire bunch, which gives a narrower bandwidth of the FEL signal and compensates for some beam arrival jitter (HHG seeds are typically limited to length of a few tenth fs at short wavelength). Nevertheless, the EE-HG can be configured to provide attosecond pulses with a synchronization of the FEL pulse to an external signal for pump-probe experiments [7].

This paper describes the initial design for a second beamline at the 250 MeV Injector [8] at PSI for proof-of-principle measurements of EE-HG seeding experiments. It will be an important step to support the EE-HG as a seeding source, in particular for the seeding option of the SwissFEL soft X-ray beamline. Note, that operation at 2 GeV implies some additional effects, which cannot be studied at 250 MeV. They arise mainly from the transport of the beam through the beamline under the effects of CSR and quantum fluctuation in the emission of hard photons of the synchrotron radiation. However the proposed EE-HG at the 250 MeV injector will answer some important question about the performance, configuration and operation of an EE-HG seeding source.

For the 250 MeV seeding beamline the following beamline components are required:

- A dogleg to steer the electron beam after compression out of the main beamline and into the EE-HG beamline.
- Two short undulators for energy modulation of the electron beam, which are resonant at a wavelength of 262 nm with a beam energy of 250 MeV.
- Two dispersive sections for compression of the induced energy modulation. The first chicane has to be significantly stronger than the second one.
- A final radiator to enhance the imprinted current modulation until saturation.
- Two laser seeds with different radiation power.
- A diagnostic port and spectrometer to analyse the harmonic beam current content in the range from 260 nm down to 5 nm.

Figure 1 shows the layout of the seeding beamline. It has to be mentioned that the simulation and configration have not been yet fully optimized yet. This will be the subject of further research.

CONFIGURATION OF THE EE-HG

The configuration is mainly driven by the wavelength of the seed signal, which is the 4th harmonic of a Nd:Yag laser at around 262 nm, and the proto-type of the U15 undulator [9] for the SwissFEL project with an undulator period of 15 mm and a K-value of 1.2. The resonant wavelength in this final radiator is 52.4 nm. That corresponds to a harmonic conversion of n=5, which is not that demanding in terms of the EE-HG performance. To test the highest harmonics, the last chicane will have a port, where synchrotron radiation is outcoupled and analyzed with a broadband spectrometer covering the wavelength range between 255 nm and 5 nm (or just 50 to 5 nm). A sufficient resolution of the spectrometer is about 1% at 5 nm. Aiming for the shortest wavelength defines the strength of the first chicane. The configuration for 52nm and 10 nm are given in Table 1.

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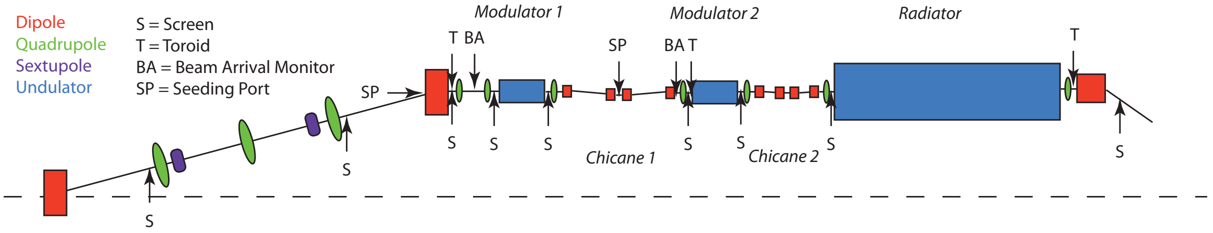

Figure 1: Layout of the EE-HG seeding beamline.

Table 1: Configuration of the EE-HG beamline for different modi of operation

Wavelength	52.4 nm	10.5 nm
Harmonics	5	25
Laser Power (1st mod.)	1.3 MW	1.3 MW
R_{56} (1st chicane)	2.01 mm	8.1 mm
Laser Power (2nd mod.)	0.14 MW	0.14 MW
R_{56} (2nd mod.)	0.41 mm	0.31 mm
Bunching	17 %	11%
Bunching (2nd harm)	6%	4.5 %

Note that the echo enabled harmonic generation always generates a secondary bunching at the doubled harmonics but with roughly half the amplitude. This can be used for reaching even higher harmonics (e.g. 5 nm with the configuration for 10 nm). For this design the modulators are modeled with a length of 80 cm, a period of 4 cm and a peak undulator value of K=2 to achieve an energy modulation of 100 and 35 keV in the two stages, respectively. With only 20 periods the implicit bandwidth of the undulators is 5%. Increasing the seed power allows to shorten the modulators. This is important for degrading effects such as the blow-up of the energy spread due to the quantum fluctuation of hard photons in the emission of spontaneous emission. However for operation at 250 MeV, these effects can be neglected. Also for a different design the modulator can be altered in K-value and period length as long as the resonant wavelength is maintained. The demands on the seed source are quite easy to fulfill when based on the design slice energy spread of 35 keV. A smaller energy spread has no degrading effect on the FEL performance, but the seed laser power needs to be increased for a larger energy spread. Also it might be more convenient to bring up the seed power level of the second modulator to the level of the first one. This would reduce the length of the second modulator by about 60%. The bunching content for the two different configurations are shown in Fig. 2.

The upper strength of the chicanes is around R_{56} = 10 mm and R_{56} = 1 mm, respectively. The electron bunch length is 0.23 ps, while the seed laser is a few ps. This allows arrival jitter of the electron bunch on the same order to guarantee sufficient longitudinal overlap.

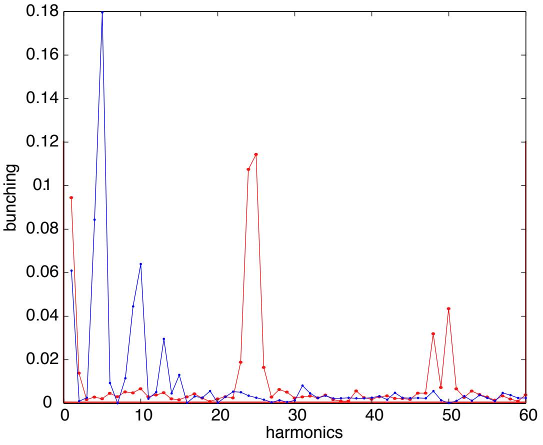

Figure 2: Spectrum of current modulation for operating the EE-HG at the 5th and 25th harmonics (blue and red curve, respectively).

FEL PERFORMANCE AT 52.4 NM

Although the EE-HG can generate a current modulation at much shorter wavelength, the test for seeding of an FEL is done at 52.4 nm, which is the resonant wavelength for the U15 prototype of the hard X-ray beamline of SwissFEL, when inserted into the 250 MeV test injector beamline. The initial bunching is strong (about 18%) and only a few gain lengths are required to reach saturation. The performance of the FEL is shown in Fig. 3, using a steady-state model for the EE-HG seeding mechanism. Note that the radiator hasn't seeded with the maximum bunching. Instead, the initial bunching was only 11% due to some non-optimal settings for the bunch compression and seeding power. Saturation occurs after 2.5 m. With the total length of 4 m for the undulator module it leaves sufficient room for degraded beam parameters. Initial studies have shown that beam emittances of up to 1.5 mm mrad, energy spreads up to 100 keV, beam deviation of about 400 microns, or energy deviation of up to 1% still allows for saturation within the undulator module.

Note that only the second modulator and chicane can be used for a simple harmonic conversion (HGHG) to the fifth harmonic, which might be useful to commissioning the beamline, the seeding pulse and the UV detection. The

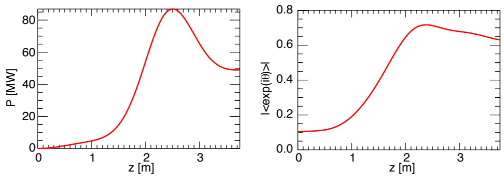

Figure 3: Radiation power and bunching at 52.4 nm in the radiator of the EE-HG seeding beamline.

real strength of the EE-HG comes with a large harmonic conversion, which cannot be tested by a radiator without excessively small periods and gaps. Therefore a secondary diagnostic for the harmonic content is highly desirable. Transition radiators become mostly transparent in the UV. Therefore the most suitable source is coherent synchrotron radiation in the last chicane. For that a spectrometer of the radiation, covering the wavelength range between 50 nm down to 5 nm is the ideal solution. An initial design of the spectrometer, including the transport optics, still has to be done.

DESIGN OF THE SEEDING LINE AT THE 250 MEV INJECTOR

Besides the essential parts of the EE-HG seeding and the final radiator, the beamline consists of 2 bending magnets to generate an offset of about 1.5m from the main 250 MeV diagnostic beam line. To keep the dispersion under control, 3 quadrupoles and two sextupoles are placed between the two dipoles. There are further quadrupoles in the beam line to control the optics and to match into the final radiator. Finally another bend steers the electron beam into a beam dump. The overall layout and the optical lattice are shown in Fig. 1 and 4.

The total length is about 17 m. The dogleg has an angle of 15 degrees over a length of 6 m to provide an offset of 1.5 m. The rest of the beamline, which runs parallel to the 250 MeV diagnostic beamline has a length of 11 m, excluding the final bending magnet and beam dump. The beamline starts at the current position of the deflecting cavity after the bunch compressor, with the 5 preceeding quadrupoles to match into the dogleg. The diagnostic beamline has to shift about 1 m downstream to make space for the first bending dipole. For the optics it is assumed that the vacuum chamber is reduced in size after the dogleg. This step is motivated by the gap sizes of the undulators, which limits the chamber to a height of about 1 cm. With a smaller vacuum chamber the bore diameters of the quadrupoles can be reduced, increasing the field strength.

The following is a list of all magnetic elements used in this beamline

- 2 Bending magnets of 40 cm length for the dogleg.
- 8 Bending magnets of 15 cm length for the two magnetic chicanes.

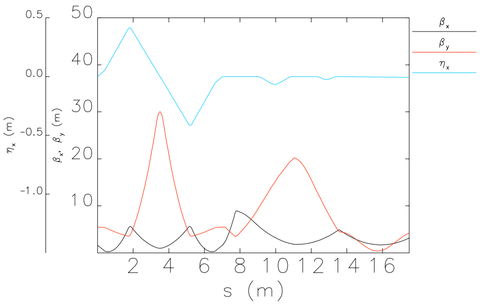

Figure 4: Optical lattice of the EE-HG seeding beamline.

- 1 Bending magnet of 40 cm length for steering into the beam dump.
- 3 Quadrupoles and 2 sextupoles of 20 cm length in the seeding beamline.
- 7 Quadrupoles of 10 cm length along the seeding beam line.
- 2 Modulator undulators of 80 cm length.
- 1 Radiator of 4 m length (U15 prototype for SwissFEL).

Some overhead has been added to the laser in comparison to Table 1 to allow for slightly larger energy spread of the electron beam or less efficient coupling to the electron beam. The seed power is 2 MW with a pulse length of at least 3 ps. We are planning to use the 4th harmonic at 262 nm of a Nd:Yag laser. The Rayleigh length of 2 m allows for suffient length to couple the laser signal into the beamline.

DIAGNOSTICS

The diagnostics for this beamline ensures: orbit control, beam matching, dispersion compensation of the dogleg, overlap with seed signal, and spectral measurement from the radiator signal. In addition to standard diagnostics (BPMs, screen monitors, current monitors) this experiment requires special diagnostics that still need to be developed. In particular, we will need to focus our attention to the beam overlap in the undulators and to tools to diagnose the longitudinal phase space of the bunches.

Transverse overlap between laser and electrons can be determined by two screen monitors installed before and after each undulator. Ce:YAG crystals can detect the laser beam as well as the electrons; should the electron beam saturate the scintillator, OTR can be used without loss of alignment. This method has been used successfully in the E-163 experiment at SLAC [10]. The screen monitors provide a destructive measurement only. However, electron position can be monitored (and stabilized) also by the BPMs installed with each screen monitor. Laser position can be stabilized by quadrant detectors behind the mirrors.

We foresee a multi-step process to establish longitudinal overlap between photon and electron bunches. The procedure will start with the first modulator and then proceed to the second modulator:

1. Establish a coarse absolute timing: OTR light from the electron beam and photons reflected from the same OTR foil are sampled by the same detector. This could be a streak camera, or possibly a multi-pixel photon counter (MPPC) connected to a fast oscilloscope. This will allow to establish the timing to an accuracy of approximately 10 ps (streak camera) or 100 ps (MPPC).

2. Establish a precision timing: Scan the laser with respect to the electron beam and observe the interaction and its effect on the beams. It is not totally obvious how to diagnose this interaction in the first modulator: the effects on the laser pulse are most likely too small to measure, the longitudinal effect after the first chicane is smeared out over several wavelengths and the projected energy spread of the electrons also does not have a significant increase above the chirp of the bunch. The only viable approach appears to be to reduce either the laser power or momentum compaction factor of the chicane, such that the electron pulse acquires a longitudinal density modulation. This could possibly be measured at a harmonic of the laser, i.e. at 131 nm.

3. Stabilize with the optical synchronization system: Use the standard bunch arrival time monitors for the electrons and a cross correlator for the laser to stabilize the arrival time with respect to the optical synchronization system.

Steps 1 and 2 were used in the E-163 experiment, albeit the laser wavelength was in this case 780 nm, which made detection of the harmonic at 390 nm more straightforward. This diagnostics will require significant work.

CONCLUDING REMARKS

We are considering to extend the 250 MeV Injector beamline to test echo-enabled harmonic generation, which is currently an option under discussion for the soft X-ray beamline of SwissFEL. The estimated length of the testing beamline is about 18 m, including a 6 m long dogleg to couple out the electron beam from the main 250 MeV beamline.

There might be the need to increase the beamline for sufficient space to hold all diagnostics, flanges, and pumps. This applies mainly for the diagnostic before the second modulator and main radiator. A shorter second modulator can partially compensate the increase when the seed power is increased to the same level as for the first modulator.

One open question is the broadband spectrometer in the wavelength range between 5 to 55 nm. The signal could be extracted from the last bend in the second chicane where the harmonic current modulation is established. Unresolved issues are: how much drift space is needed to separate the synchrotron radiation from the electron beam and whether it can be deflected under a large angle towards the spectrometer. Alternatively, it should be studied, whether the signal can be propagated through the radiator with a diagnostic station after the final bend.

In conclusion it is highly desirable to verify the performance of echo-enabled harmonic generation with experimental results. This would pave the way of this scheme as the preferred method of seeding for soft X.ray FELs. For the case of SwissFEL this test of the seeding scheme would be the decisive factor to select the seeding scheme at the soft X-ray beamline Athos.

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