# PROSPECTS OF THE BESSY HIGH-ENERGY-FEL *

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*Abstract*

BESSY proposes a linac-based High-Gain Harmonic-Generation (HGHG) free electron laser (FEL) facility with three independent FEL lines. In the BESSY High-Energy-FEL (HE-FEL), the seed laser wavelength of 279 nm is downconverted to 1.24 nm by a cascade of four HGHG-stages. This procedure requires a high brightness electron beam and a high power seed laser. With the nominal set of beam parameters as detailed in [1], radiation power in the range of GWs can be achieved. However, the signal to noise ratio degrades in each HGHG stage. This motivated intensive studies on the possibilities to further optimize the performance of the BESSY HE-FEL. In this paper, we report on three methods aiming to control the signal to noise ratio. They include simulation studies of new seeding schemes with HHG-lasers at shorter wavelengths and seeding with higher seed powers. Also, a concept for the integration of monochromators between two HGHG-stages has been worked out, see also [2]. All methods were studied extensively with regard to their influence on FEL output power, pulse duration and spectral bandwidth.

## INTRODUCTION

BESSY proposes to build a Soft X-ray FEL facility with a Low-Energy, Medium-Energy and High-Energy-FEL (HE-FEL) line. The HE-FEL uses a cascade of four HGHG stages to downconvert the initial seed wavelength of 279 nm to an output wavelength as low as 1.24 nm. In each stage, seed radiation and electron beam interact in an undulator called modulator. This leads to an energy modulation of the electron beam which then travels through a magnetic chicane where the energy modulation is turned into spatial modulation (bunching). The bunched beam is then inserted in a second undulator, called radiator, set to a higher harmonic of the seed frequency. At the end of the radiator, the short wavelength pulse can be extracted and used as the seed for the next stage. In between two stages, a second magnetic chicane provides for a 100 fs temporal delay so that the seed will interact with a fresh part of the electron bunch in the subsequent modulator [3]. The output pulse of the last radiator is then inserted into a so called final amplifier tuned to the same resonant frequency. In the final amplifier, the FEL process is brought to saturation.

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### *Coherence Degradation in Harmonic Cascades*

In HGHG-schemes that aim at reaching the X-ray wavelength range starting from visible or UV light, shot noise effects are an important issue. According to [4], in harmonic cascades the signal to noise ratio (SNR) decreases by the square of the harmonic number

$$\left(\frac{P_s}{P_n}\right)_{out} = \frac{1}{n^2}\left(\frac{P_s}{P_n}\right)_{in}. \tag{1}$$

Thus in the case of the BESSY HE-FEL where a factor of 225 is neccesary to convert the seed wavelength down to the output wavelength, noise degradation of the radiation properties can be severe. In order to best conserve the excellent temporal coherence of the BESSY FEL radiation, the SNR has to remain large. According to Eq. 1, we can improve $(P_s/P_n)_{out}$ by either decreasing the frequency-conversion factor n or by enhancing the input signal to noise ratio $(P_s/P_n)_{in}$.

## CONSERVATION OF TEMPORAL COHERENCE

In this paper we report on three ideas that were investigated recently to stabilize temporal coherence in the BESSY HE-FEL. One application aims at reducing the number of FEL stages with only an overall factor 45 in harmonic conversion neccessary. This can be done by implementing a Higher Harmonic Generation (HHG) laser source as the initial seed laser. Alternatively, when the number of HGHG stages remains unchanged, the signal tonoise ratio has to be improved through other means. One option is to provide for a strong increase of the input SNR. The signal to noise ratio at the beginning of the modulator is given by the ratio of seed power to background radiation and can thus be increased by seeding the FEL with higher seed power. This scenario was investigated assuming a peak initial seed power of 1 GW keeping the remaining seed properties constant. The third option is filtering with the aim to counteract the noise build-up of the first HGHG stage. This was done by monochromizing the output radiation before using it as a seed in the second modulator. The monochromization scheme and neccessary electron bypass are reported in length in [2]. For all three methods, 3D-FEL simulations of the entire HE-FEL line were performed with GENESIS [5]. We will discuss the impact of all methods on the HE-FEL output and compare their influence on critical properties such as pulse energy, peak power and spectral bandwidth.

### *Seeding with HHG Lasers*

Higher Harmonic Generation lasers make use of strong nonlinear interaction effects in gases that excite a vast range of odd higher harmonics of the pulse optical frequency. Recent experiments show that the efficiency of HHG lasers in the EUV range could be improved greatly using Ti:sapphire laser sources in combination with Xenon [6, 7].

For a seeded FEL, the seed laser power is essential. It has to be large enough to overcome the shotnoise level of the electron beam, especially with regard to the SNR. The required peak power depends on the FEL resonant wavelength and electron beam parameters. For each of the HE-FEL stages, the neccessary seed power levels can be estimated analytically. At 55 nm, the wavelength that is used to seed the nominal HE-FEL stage two, it can be derived that a peak power of 100 MW is sufficient to start the FEL process efficiently since the harmonic number is reduced. In the above mentioned experiments, HHG pulse energies in the range of 1-2$\mu$J could already be verified. Thus for a very short seed pulse of about 10 fs, a peak power of 100 MW can in fact be derived. This also agrees with measurements of the HHG photon output produced on the 15th harmonic of an 800 nm laser field reported in [8].

When using such a 100 MW-HHG pulse and starting the BESSY HE-FEL from the 55 nm-stage that was formerly the second HGHG stage, a few modifications are required. Note that the seed power is now considerably lower than in the nominal case, so that sufficient energy modulation can only be acquired when doubling the length of the next stage modulators. Keeping the radiator parameters unchanged and regarding the output power at the end of the final amplifier, Fig. 1, top, the BESSY HE-FEL now produces a peak power in the range of several GWs. Compared to the nominal output reported in [1], this is an increase in peak power by about a factor 5. The power distribution depicted in Fig. 1 verifies an improvement in temporal coherence as well. The spectral bandwidth, see Fig. 1, bottom, has been reduced by the remarkable amount of 60%.

### *Seeding with 1 GW Seed Power*

In order to increase the input SNR of the BESSY HE-FEL, a higher seed power was used. For the simulations, a seed pulse with 1 GW peak power and an rms width of 10 fs was assumed. Note that this is a factor two increase in peak power compared to the nominal HE-FEL simulations in [1]. While all undulator properties were kept the same, some of the dispersive sections had to be adjusted for optimal bunching in the radiators. Figure 2 shows the effects of high power seeding on the temporal and spectral distribution of the output radiation pulse. It shows that there is merely a small influence on temporal coherence and spectral bandwidth. Still, the number of spikes in the temporal power distribution has decreased noticeably and there is a reduction of spectral bandwidth by 35%. Note that the pulse length has also decreased. This can be explained by the alterations of the dispersive sections. There, the magnetic field strengths had to be turned down to avoid overbunching due to the higher seed fields. The energy modulated parts of the beam thus turned into shorter prebunched sections, emitting shorter radiation pulses [9].

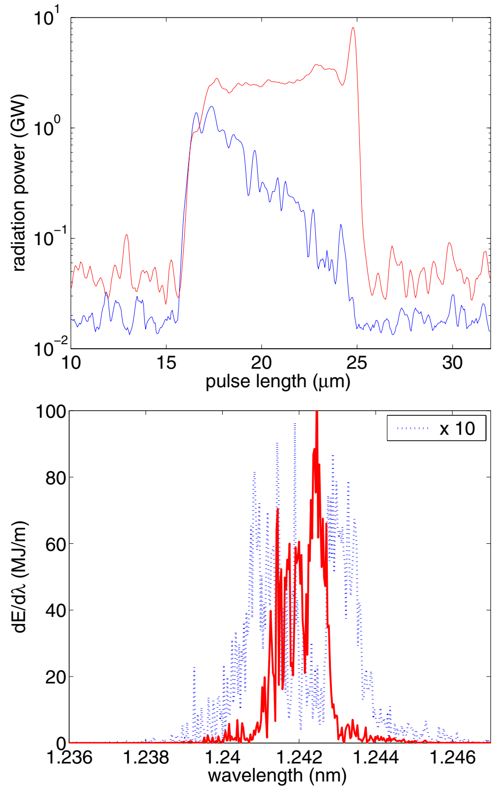


Figure 1: Radiation pulse and spectral power distribution at end of BESSY HE-FEL final amplifier when using HHG-laser seed at 55 nm, red, reducing the number of HGHG stages to three. Results compared to nominal seeding scheme with UV-source and four full HGHG-stages.

### *Using Radiation Filters*

In order to filter the radiation spectrum in between two HGHG stages, a monochromization scheme of the first stage output pulse was conceived. It makes use of a non-dispersive double-monochromator that allows to filter out part of the radiation pulse with regard to a certain central wavelength. While the seed pulse is thus effectively narrowed in spectral bandwidth before being inserted in the next stage with only a minor increase in pulse length, the electrons have to be sent through a bypass chicane. The electron bypass was conceived such that it requires roughly 23 m in length and inflicts no degradation of the beam emittance or energy-spread [2].

In order to use this method efficiently, the first radiator had to be extended in length by almost a factor three in order to yield sufficient output powers due to the expected power reduction of the monochromator. In addition, the stage two and three modulators were extended by a factor two for the same reason as detailed in the HHG laser seeding option.

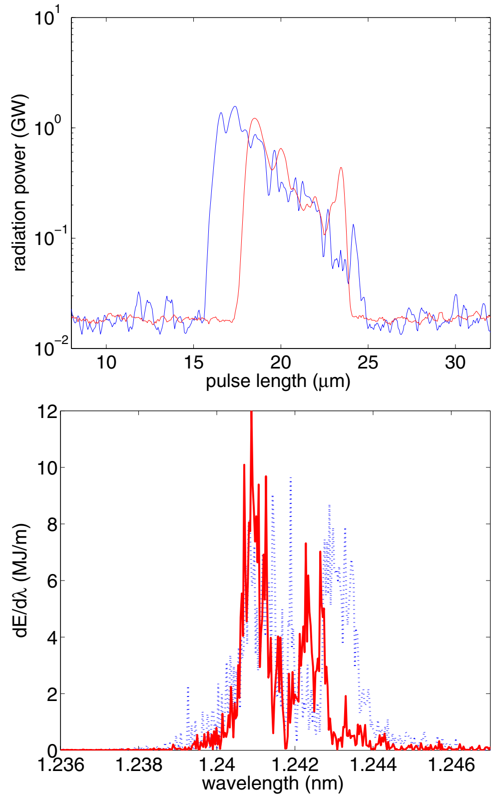


Figure 2: Radiation pulse, top, and spectral power distribution, bottom, at end of BESSY HE-FEL final amplifier when using twice the initial seed power at 279 nm, red, compared to using nominal seed power of 500 MW, blue.

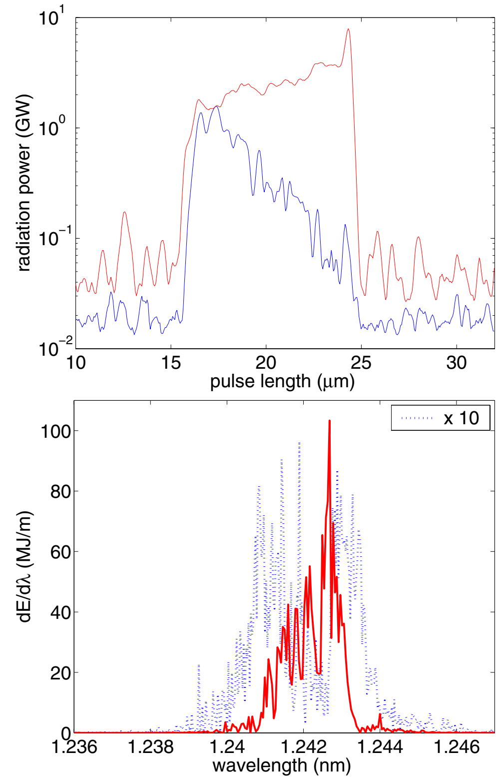


Figure 3: Radiation pulse and spectral power distribution at end of BESSY HE-FEL final amplifier when using carefully optimized monochromator in between stage one and two, red, compared to nominal output without filtering.

Figure 3 depicts the temporal and spectral power distribution that is achieved at the end of the final amplifiers when using the monochromator in between stage one and two. It shows that the increase in pulse power and energy is well above a factor five and that the spectral bandwidth is about halved compared to the nominal case.

From start to end simulations [10] of the BESSY FEL injector and linac it is known that the first stage radiation properties are subject to variations in peak power and central wavelength. Thus for the monochromizing option, the required tuning range has yet to be shown.

## COMPARISON OF RESULTS

Table 1 compares the key output parameters of the HE-FEL that are obtained using the three options explained above. Note that the term relative bandwidth refers to the 3dB-bandwith, i.e. the full width half maximum value of the spectral distribution and is taken relative to the bandwidth of the nominal HE-FEL. It was calculated using a Gaussian fit to the spectrum. Table 1 shows that the reduction of spectral bandwidth is remarkable for all methods, while the pulse energy can also be increased significantly using either filtering or HHG seeding. We also found that with the HHG seeding and the monochromizing option, saturation in the final amplifiers could be attained several meters earlier than nominally forseen, see Fig. 4. However, HHG lasers today lack tunability and stability neccessary for the application in seeded FELs. As work in the field of HHG lasing is progressing whith great results, though, they remain the most interesting option for the BESSY HE-FEL.

Table 1: Relative bandwidth BW, total pulse energy E and pulse peak power P of the output pulses when comparing the different methods to the nominal HE-FEL properties that are detailed in [1].

| | **rel. BW [%]** | **E [$\mu$J]** | **P [GW]** |
|---|---|---|---|
| nom. HE-FEL | 100 | 16.3 | 1.6 |
| 1 GW seeding | 65 | 11.3 | 1.2 |
| monochromator | 48 | 82.5 | 7.9 |
| HHG seeding | 39 | 88.5 | 8.1 |

## CONCLUSION

It could be shown that the BESSY HE-FEL output can be improved significantly when the shot noise related degradation of temporal coherence is counteracted efficiently. Three options including alterations of the initial seed pa-

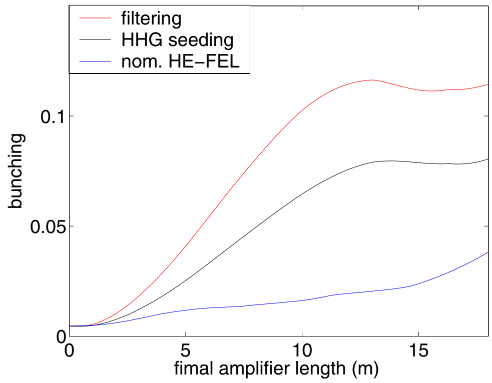


Figure 4: Evolution of microbunching in the HE-FEL final amplifier when comparing the filtering option using a monochromator, red line, and the HHG seeding option, black line, to the nominal case, blue.

rameters and incorporating a monochromator in between two FEL stages were investigated. In preliminary studies we found that all three methods show the capability of significantly reducing the spectral bandwidth of the output radiation. Filtering with monochromators and the HHG seeding option also yield an improvement of the output pulse energies. In future simulations, the applicability of the monochromator will be studied further and the results of recent start-to-end-simulations [10] of the BESSY FEL injector and linac should also be taken into account.

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