COHERENCE IMPROVEMENTS OF THE BESSY HGHG FEL RADIATION*

M. Abo-Bakr†, R. Follath, A. Meseck, BESSY, Berlin, Germany

Abstract

The Berliner Elektronen Speicherring Gesellschaft fuer Synchrotronstrahlung (BESSY) proposes to build a Soft X-ray free electron laser (FEL) multi-user facility. It will consist of three FEL-lines, each based on a cascaded High-Gain Harmonic-Generation (HGHG) scheme. With seed lasers, tunable between 230 nm and 460 nm, the output radiation wavelength ranges from 1.24 nm to 51 nm.

As the noise to signal ratio increases quadratically with harmonic number, the coherence of the output radiation degrades for very high harmonics. For the short-wavelength BESSY-FEL line, operating on harmonics $h \leq 225$ of the seed, a cure to this effect is of interest. One possibility to maintain the excellent coherence properties of the laser seed is to monochromatize the radiation output of the first HGHG stage, which is the seed radiation for the second stage. This can be done by means of a "non-dispersive double-monochromator" system, placed in between the two HGHG stages. Layout and parameters of this monochromator section are described.

To separate the electron beam path from the monochromator's optical devices a bypass section is needed. Its design is presented and influences on the electron beam dynamics are discussed.

Simulations of the full cascaded HGHG FEL, using the monochromatized seeding radiation and the bypassed electron beam, are presented.

INTRODUCTION

BESSY operates synchrotron light sources for more than 25 years. In addition to the existing 3^{rd} generation light source BESSY proposes a Soft X-ray FEL multi-user facility [1], driven by a superconducting 2.3 GeV CW linac. Three independent FEL-lines will cover the wavelength range from 1.24 nm to 51 nm.

To deliver ultra short pulses and to ensure a high pulse to pulse stability the High-Gain-Harmonic-Generation (HGHG) principle [2] will be applied. In this approach a seed from an external high power fs-laser and the electron bunch propagate through an undulator (modulator). If the seed laser wavelength equals the modulator's fundamental resonance wavelength an energy modulation is induced, which is transformed into a spatial, longitudinal density modulation in a subsequent dispersive section. As the density modulation also contains harmonics of the seed laser wavelength these micro-bunches will emit coherently in a subsequent undulator (radiator), tuned to be in resonance to a specific seed laser harmonics. The resulting photon output can be used as the seeding field for a next stage of a cascaded HGHG scheme. As the electron bunch quality significantly degrades due to the seeding and amplification process, the fresh bunch technique[3, 4] is applied in each HGHG stage, to avoid degradation of the FEL process. Finally the HGHG scheme delivers short wavelength photon pulses, where the external seed laser dominates the statistical noise features from self amplified spontaneous emission and determines pulse durations and stability.

At very high harmonics the coherent properties of the HGHG output suffer from the shot noise of the electron beam [5]. The noise to signal ratio increases proportional to the square of the harmonic number causing a coherence degradation of the output radiation. To reach the shortest wavelength of 1.24 nm, offered by the BESSY Soft X-ray FEL, a harmonic number of $h = 225$ has to be used, to down convert the seed's wavelength of 279 nm.

Shot noise caused effects can be reduced by introducing spectrum cleaning between the first and second HGHG stage of the short wavelength FEL line. A "non-dispersive double-monochromator" has been designed for this purpose. A symmetrical arrangement of two spherical gratings, two toroidal mirrors and a slit build up this monochromator system, as shown schematically in Figure 1. To separate the electron beam path from the optical devices a magnetic bypass chicane is applied.

Although the method of operation for the monochromator are different, the hardware setup of the monochromator and bypass section are similar to those of the "Self-Seeding Option" of TTF II [6, 7].

In this paper we describe layout and parameters of the applied monochromator section. The design of the electron bypass chicane is presented and influences on the beam dynamics are discussed. Finally simulations of the short-wavelength FEL-line, using the monochromatized seed radiation and the bypassed electron beam, are presented.

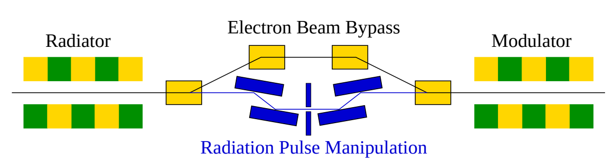

Figure 1: Coherence improvement setup with monochromator and electron bypass.

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† e-mail: Michael.Abo-Bakr@bessy.de

THE MONOCHROMATOR SECTION

The output of the first HGHG stage shows spectral noise features which are modified to improve the radiation quality, used as seed for the second stage of the HGHG scheme. The monochromator should trim the pulses without lengthening them beyond the Fourier transform limit. The cycle duration of light with 24 eV is already 0.16 fs, whereas typical pulse lengths are in the order of 20 fs.

The high fluence of the FEL and the low normal incidence reflectance in the VUV suggest the use of grazing incidence optics for the beamline design. Consequently deflection angles of 172° were chosen for all optical elements.

The beamline consists of a dispersion-less double monochromator in a 4f-setup [8], as shown in Figure 2. Its first part sets the wavelength dispersion in the intermediate focal plane where a slit selects the required bandwidth. The second part is simply a mirror image of the first one and reverses the pulse dilatation introduced by the first one. A photon energy changes are accomplished by a simultaneous rotation of both gratings. Output pulse length and bandwidth are selected by means of the intermediate slit width: wider slits correspond to shorter pulses with larger bandwidths.

Each monochromator is designed as a spherical grating monochromator, where the grating structure has a varied line spacing. Parameters of the first grating are chosen to collimate the incident light in the dispersive plane at three photon energies namely 12 eV, 24 eV and 30 eV, respectively. The subsequent toroidal mirror focuses the diffracted light onto the slit. In this geometry the grating is located in the front focal plane of the mirror and the slit in the back focal plane. Together with the second part of the beamline a 4f-setup is realised. In this beamline design the focusing condition is perfectly fulfilled at the design energies, whereas in between a small defocusing occurs.

In the horizontal plane, the light is collimated by the mirror when the grating is set to 24 eV. Due to the rotation of the spherical grating in an energy scan, there is a small variation in the axial position of the horizontal focus in the subsequent FEL. The variation is below 1 mm between 10 and 30 eV, which is small compared to the Rayleigh range of 900 mm . The optical path length through the monochromator is 19.80 mm longer than the straight line and does not change when the photon energy is varied.

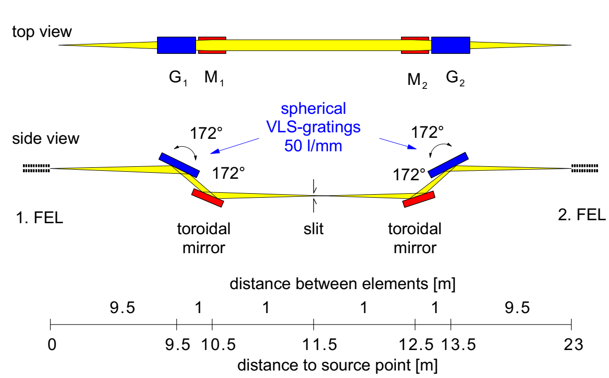

Figure 2: Layout of the dispersion-less double monochromator setup.

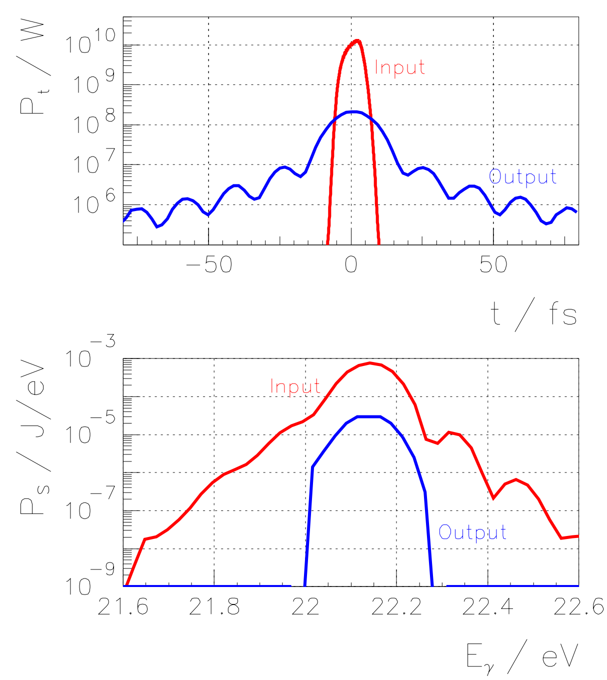

Figure 3: Monochromator input (red line) and output (blue line) power in temporal (upper graph) and spectral (lower graph) domain.

For the ray-tracing a transverse and longitudinal Gaussian shape of the source is assumed, with $\sigma = 60\,\mu$m beam size, $\sigma' = 69\,\mu$rad beam divergence (RMS) and 6 fs (FWHM) pulse duration. Figure 3 shows the monochromator output for a 300 μm slit. Due to limited reflectance of mirrors and gratings the power is reduced by about two orders of magnitude. The bandwidth is reduced to 250 meV. Correspondingly, the pulse is lengthened to 16 fs (FWHM). The pulse shape behind the monochromator shows secondary maxima due to the spatial slit diffraction pattern, converted to a temporal pattern by the second grating.

THE ELECTRON BYPASS SECTION

The electron path with its deflecting and focusing magnets has to be separated from the radiation path with the optical devices of the monochromator section. This can be achieved by using a magnetic chicane. Beside the separation the bypass section has to fulfill several other tasks and requirements:

- The electron beam path length has to be adjusted to the light path length to guarantee the overlap of the monochromatized seeding radiation field and the electron bunch in the downstream modulator. In addition, the ”fresh bunch” shift has to be generated by the bypass chicane.

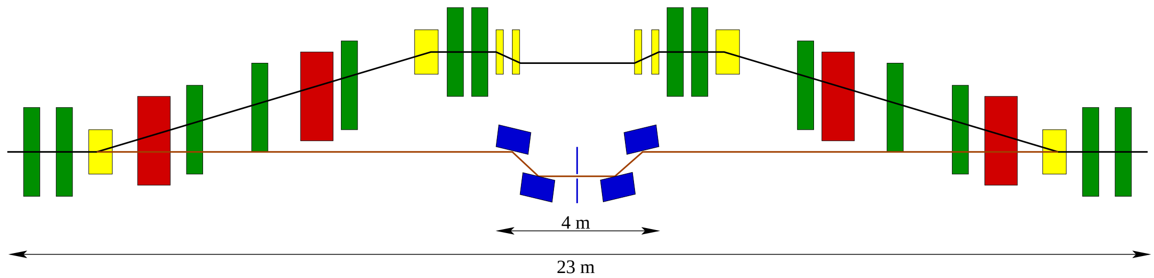

Figure 4: Draft of the electron bypass with dipole (yellow), quadrupole (green) and sextupole magnets as well as the optical devices (blue).

Table 1: Parameters of the electron bypass section.

type	4 bend main chicane
total length / m	23.1
length of main bendings / m	0.4
angle of main bendings / °	3.4
R_{56} / m	$9.6 \cdot 10^{-4}$
no. quadrupole magnets	14
no. sextupole magnets	4
path length increase / m	0.1980
transverse separation / m	0.338

- As the bunch compression leaves a significant momentum chirp on the electron beam, a nearly isochronous ($R_{56} \approx 0$) bypass optics will be needed, to avoid changes from optimal bunch length and peak current values.
- At short bunch lengths and high peak currents coherent synchrotron radiation (CSR) can potentially increase energy spread and transverse emittance. To suppress CSR induced bunch quality deteriorations, short, small angle bending magnets are applied in an lattice with optimized beta functions.
- The momentum chirp also causes a large projected energy spread. To avoid emittance dilution due to momentum depending focusing the chromaticity of the bypass has to be corrected carefully.
- For space and economical requirements a short bypass section with few magnetic elements of reasonable strength is desirable.

A magnetic lattice that meets all mentioned demands has been designed on base of a symmetrical 4 bending chicane. Parameters of the electron bypass are summarized in Table 1, beta functions and dispersion are shown in Figure 5.

For a fixed bending angle, which should be small with regard to CSR effects, the space between the first and second dipole magnet results from the required electron to light path length adjustment. Space requirements of the magnet optics in between these dipoles sets the lower limit for the length to about 6 m. The corresponding transverse separation of electron beam path and optical monochromator elements exceeds the required value ($\approx 40\ mm$) by far.

To get a low R_{56} value, the dispersion must be small in all bending magnets. It is controlled by two strong focusing quadrupole magnets placed between first and second bend, tuning the dispersion to zero at the second dipole's exit. Each of these achromatic sections contains additionally two sextupole magnets to control the chromaticity and one quadrupole magnet to optimize beta-functions. To match the outer twiss parameters a quadrupole doublet at the begiining and end of the bypass section has been applied. For a fine-tuning of the electron path length without changing the trajectory in quadrupole or sextupole magnets, there will be a second simple chicane between the two achromats, build up from four small dipole magnets.

Tracking studies through the introduced lattice have been performed, to verify the conservation of electron beam quality. ELEGANT [9] simulations show a small increase of the projected emittance in the order of (1-2)%, while the sliced emittance is unchanged. The bunch length is slightly reduced, due to the chicane's R_{56}, while the energy spread remains constant.

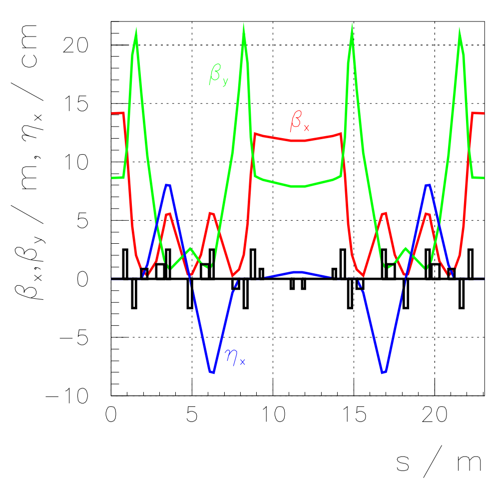

Figure 5: Twiss parameter along the electron bypass. red: β_x, green: β_y, blue: η_x.

FEL SIMULATIONS

All simulations have been performed for the short wavelength FEL-line, using the 3D-code GENESIS [10].

Due to the limited transmission of the monochromator section on the percent level (see Figure 3), the first radiator has to be extended from 3.7 m to 9.2 m to deliver sufficient seed power for the second HGHG stage. In addition, the length of the second and third modulator is increased from 2.0 m to 3.7 m and from 2.1 m to 4.2 m respectively. With respect to the full HGHG cascade no changes are required for the frequency up conversion scheme, i.e. the sequence of applied harmonics. A seed laser pulse of 3.5 fs length and 30 μJ pulse energy has been used for this simulations.

For ray-tracing through the monochromator line the radiation output of the first extended HGHG stage has been parameterized, assuming a transverse and longiyudinal Gaussian distribution. The monochromator output has been parameterized again with the same assumptions and used as input for the next stage's seed radiation.

As the bypass tracking simulation verify, that the beamline is nearly transparent and the bunch quality practically unaffected, an unseeded, fresh bunch part from the first stage's output has been used as input for the second HGHG stage. Simulation procedure up to the end of the HGHG cascade is unchanged.

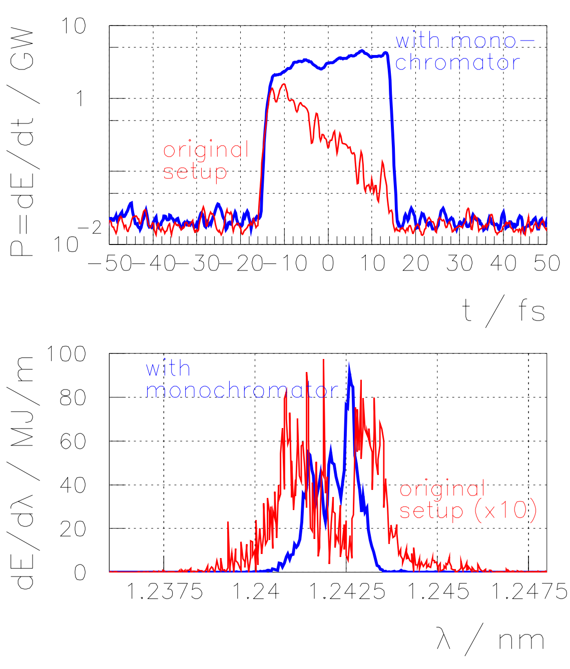

Figure 6: Simulated output performance of the short wavelength FEL-line: Power in temporal domain (upper graph) and in spectral domain (lower graph). Red line: original case without monochromator, Blue line: with monochromator and adjusted undulator lengths.

Saturation in the final amplifier is reached at 14 m, compared to about 18 m for the monochromator-less HGHG cascade. Figure 6 compares the output performance for both cases. The total pulse energy (90 μJ) is increased by a factor of 5.5 and peak power is roughly doubled with the monochromator, while the bandwidth is nearly halved with a spectral peak power increased by about one order of magnitude.

CONCLUSION

In cascaded HGHG schemes, using very high harmonics, degradation of the coherence of the FEL output has to be considered, resulting from shot noise effects. A possibility to improve the output quality is a ”dispersion-less double monochromator”, cleaning the spectral power output after the first HGHG stage. FEL simulations for the adjusted, short wavelength BESSY Soft X-ray FEL-line show a significantly increased output power with a nearly halved bandwidth in this case.

So far only parameters of the radiation and the electron beam have been shared between the ray-tracing, electron tracking and FEL simulation tools. In a next step simulations should be done, using more details or even the complete distribution of the radiation field and the electrons.

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