OUTPUT PERFORMANCE OF THE STARS HGHG DEMONSTRATOR AT BESSY*

B. Kuske †, K. Goldammer, A. Meseck, BESSY, Berlin, Germany

Abstract

BESSY is planning to construct a free-electron laser facility, STARS - **S**uper conducting **T**est-**A**ccelerator for **R**adiation by **S**eeding, to demonstrate cascaded high-gain harmonic generation (HGHG) FELs. A 325MeV superconducting linear accelerator will drive two HGHG-stages, where the second stage is seeded by the radiation from the first stage. Such a cascading of the HGHG scheme allows for a reduction of the STARS output wavelength down to the few 10nm range. This paper describes the layout and the expected performance of the facility, the achievable wavelength range, the harmonic content of the radiation, the potential of super-radiant pulses and first tolerance studies for bunch parameter mismatch.

INTRODUCTION

In 2004, BESSY presented the Technical Design Report for a 2.25GeV linac driven Free-Electron Laser (FEL) user facility, covering the VUV to soft X-ray spectral range [1]. The facility utilizes the high-gain harmonic generation principle (HGHG), first demonstrated at Brookhaven National Labratory, USA, in 2000 [2]. In order to reach the short wavelength range, several cascaded HGHG stages are foreseen. In 2006, the German Science Council recommended the construction of a demonstrator to investigate the possibility of cascading HGHG stages. A Conceptual Design Report for this demonstrator, 'STARS'- **S**uper conducting **T**est-**A**ccelerator for **R**adiation by **S**eeding, has been published in 2006 [3]. STARS will consist of a normal conducting RF gun, a superconducting 325MeV linac, a collimation and diagnosis section and a 27.5m undulator section [4]. It will produce pulses in the spectral range from 18eV to 31eV. For further details see [5]. This paper details the layout of the undulator section and presents the performance of STARS at different wavelengths and operational modes. A few preliminary calculations concerning the stability of the machine are shown.

MECHANICAL LAYOUT OF THE UNDULATOR SECTION

The undulator section will consist of two HGHG stages separated by a fresh bunch chicane, that delays the electron bunch so that the radiation of the first stage seeds a preceeding, fresh part of the beam. Each stage starts with a short undulator to modulate the energy of the electron bunch (modulator). It is followed by the dispersive section consisting of four identical dipoles. The adjacent undulator, called radiator, consists of two respectively three separated segments tunable to the harmonics of the modulators' resonant frequency. Table 1 lists the important parameters for all four undulators.

Table 1: Characterization of the STARS undulators (Modulators: M1, M2, Radiators R1, R2.)

Type	**M1** planar	**R1** planar	**M2** planar	**R2** Apple III
Period [m]	0.05	0.05	0.05	0.022
No. Periods	10	2*40	30	3*150
Aper. [mm]	10	20	20	7
Max. B_y[T]	1.1	1.1	1.1	0.839
Max. B_x[T]	-	-	-	0.621
Length [m]	0.5	2* 2.0	1.5	3*3.3
Res. λ [nm]	800	160/200	160/200	40/50/66

The fresh bunch chicane is mechanically identical to the dispersive sections. In order to control the electron beam size along the length of almost 30m, a total of 9 quadrupoles are distributed, one before and after each chicane and one in between undulator segments. The matching into the section will be handled in the preceding collimator. The total length of the chicanes is 2.5m; the distance between undulator segments is 1.0m. The chicanes will also host all necessary diagnostics, as well as all vacuum components, which shall not be incorporated into the undulators. Phase shifters and further diagnostics are placed between undulators segments. The correctors necessary to control the trajectory of the bunch are incorporated into the quadrupoles.

OPERATIONAL MODES

A tunable 800nm Ti-Saphir laser will be used to seed the first modulator. There will be a small chicane right in front of the modulator as a port for the beam. The 4th or 5th harmonic of the beam modulation can be amplified in the following radiator by tuning the dispersive section and driving the undulator gap. After the radiator the electron bunch is delayed by 100 fs in the fresh bunch chicane. Thus, in the second modulator, the preceding, unused part of the bunch is seeded by radiation 160nm and 200nm. The second radiator can be tuned to the 4th or 3rd harmonic of the resonant frequency of the second modulator, so that the final output

* Funded by the Bundesministerium für Bildung und Forschung (BMBF), the State of Berlin and the Zukunftsfond Berlin
† Bettina.Kuske@bessy.de

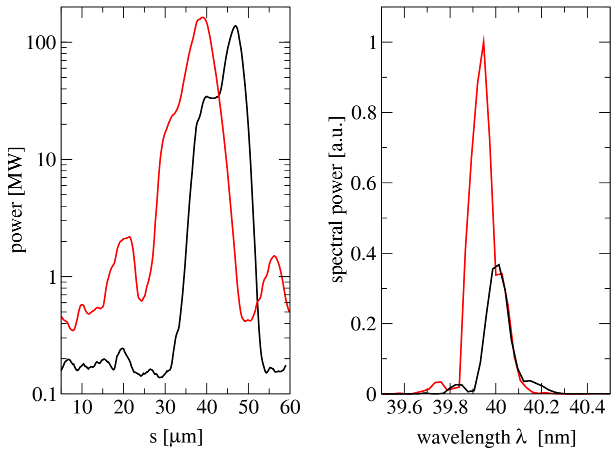

Figure 1: The temporal and the spectral power, at 40nm and helical polarization, when optimizing the output of the first radiator segment (black) and the second segment (red).

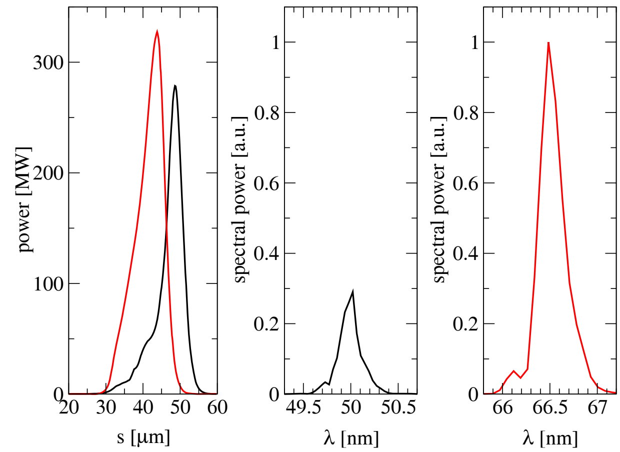

Figure 2: Temporal and spectral power at 50nm (black) and 66nm (red) for planar radiation, optimized for the first radiator segment.

ranges from 40nm to 66nm. Despite changing the combination of the harmonics, the tunability of the seed laser frequency allows for delivering any intermediate frequency. The second radiator consists of three undulator segments. Depending on the final bunch parameters and the chosen wavelength, the saturation length varies, and the gaps of one or two segments might be opened for certain operating conditions. The second radiator will be an APPLE III type undulator [7], so that the polarization is variable. Due to the segmented layout of the radiators and the tunability of the dispersive sections, a wide range of operational modes are feasible. By increasing the fields in the chicanes, the FEL process can be pushed to saturate at the end of the first segment of Radiator 2, with a very good signal to noise ratio of 10^3. The saturation point moves towards the end of the second segment of Radiator 2, when the chicane strength is relaxed. Higher temporal as well as a much higher spectral power can be reached, at the expense of a smaller signal to noise ratio, see Fig 1.

Furthermore, the tolerance of STARS to bunch parameter deviations, like the finally achievable emittance or the energy spread is largely increased. Best results for a bunch emittance of 1.0 πmm mrad e.g. are reached by using only one segment of Radiator 1. In this sense, the following performance characteristics are only examples of what is achievable.

PERFORMANCE

All calculations presented have been performed using GENESIS1.3 [6]. As the performance strongly depends on the bunch parameters, only start-to-end bunches, i.e. results from particle tracking studies in the gun, linac and collimator were used as input for the performance calculations. The dispersive chicanes were modeled using the transfer matrix feature of GENESIS and the bunch part used in the second stage has also been tracked through the first HGHG stage, to include any possible spontaneous radiation effects. The bunches are seeded at 800nm by a 275MW, 30fs Gaussian shaped seed pulse. The average sliced emittance extracted from the start-to-end simulation is 1.0 πmm mrad, a value much smaller than measured so far in state-of-the art normal conducting guns for 1nC bunch charge. On this account, the sliced emittance of the bunches has been raised to 1.5 πmm mrad. The averaged bunch parameters are listed in Table 2.

Table 2: The main average bunch parameters vary slightly for the two bunch parts used in the two stages

	part 1	**part 2**
Gamma	639.6	638.5
Emittance$_{x,y}$ [π mm mrad]	1.44	1.50
Rel. energy spread	3.3 10^{-5}	3.1 10^{-5}
Beam size$_{x,y}$ [μm]	126, 118	130, 134
current [A]	508	512
total bunch charge [nC]	1.0	

The calculations do not include any magnetic errors or trajectory offsets, except for those inherent to the bunch, or any bunch-to-bunch fluctuations.

Fig. 2 shows the temporal and spectral power for 50nm and for 66nm and planar polarization taken behind the first radiator segment. In order to switch from 50nm to 66nm only the second radiator has to be re-tuned to the third harmonics of 200nm. Due to the increased undulator K-value the power increases. For the longer wavelengths it becomes increasingly difficult to suppress the background radiation and avoid the onset of super-radiance to maintain a pure spectrum when optimizing the output of the second radiator segment.

Table 3 displays the three main operational modes and their performance parameters optimized for clean spectra and maximal power. Any intermediate wavelength can be achieved by varying the seed laser wavelength and adjusting the undulator gaps.

Table 3: Main STARS performance parameters for planar (P) and helical (H) polarization.

Wavelength	**40nm**		**50nm**		**66nm**
Polarization	P	H	P	H	P
No. segments	2	2	1	1	1
Power [MW]	120	163	275	336	328
Pulse energy [μJ]	2.8	3.8	6.1	7.4	9.2
Pulse width [fs]	18	19	16	16	24
% of pulse energy in 0.1 % bandwidth	53	53	41	41	23
background energy / pulse energy [%]	6.6	5.9	6.6	7.1	2.3

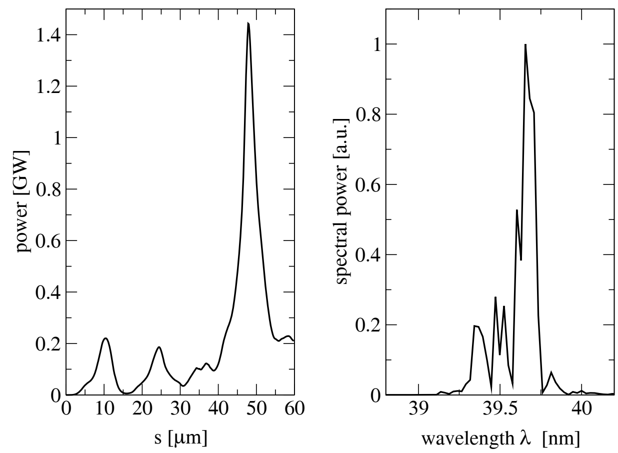

Figure 3: Temporal and spectral power of the super-radiant pulse at the end of the third radiator segment. Still 40% of the power are located within 0.1% bandwidth. The FWHM pulse length is 14fs.

The FEL power can be increased beyond saturation by slightly detuning the undulator. This leads to the onset of the super-radiant regime, [8]. The coherence length, i.e. the slippage within one gain length, becomes comparable to or larger than the pulse length. When the radiation power is high enough, bunching occurs instantly in a small fraction right ahead of the pulse, the power is further increased and the electrons immediately debunch again. As a result, much higher peak powers at very short pulse lengths can be achieved, at the expense of a deteriorated spectral purity. Fig. 3 displays the results achievable at 40nm planar polarization and an emittance of 1.0 πmm mrad taken behind the third undulator segment, when the undulator K-value is reduced by 1.7%. The peak power is 1.4GW, the pulse energy is 43μJ. Despite the deteriorated spectrum, still 40% of the energy is located within 0.1% of the spectral bandwidth. The FWHM pulse length is 14fs.

SENSITIVITY TO BUNCH PARAMETERS

In preliminary tolerance studies, the sensitivity of the STARS performance to large changes of single bunch parameters has been studied for the most sensitive case at 40nm and planar polarization. These calculations model basic parameter deviations, e.g. when the calculated energy spread or the emittance differ from the predictions. In this case, the undulator section can be adjusted to achieve the best performance under the given conditions. To achieve the following results, the structural flexibility of STARS as explained above has been exploited. In order to preserve the typical variation of the parameters over the bunch, the parameters have been scaled for each slice. Please note that the expected shot to shot parameter variations are much smaller than the given offsets. Shot to shot fluctuations can not be counteracted and have to be studied separately. The most critical parameters for the performance are the emittance, the energy spread and the current. Their values and the maximum output power are listed in Table 4.

Table 4: Maximal achievable power, in case major bunch parameters should not match the predictions. The reference values are indicated by italic letters. By using the second radiator segment, even the 68MW reached for an emittance of 2.0 πmm mrad could be improved.

Parameter	**Value**	**Segment**	**Peak power [MW]**
Emittance	1.0	1	145
[πmm mrad]	*1.5*	*1*	*120*
	2.0	1	68
Rel. energy spread	*3e-5*	*1*	*120*
	1e-4	2	127
current [A]	450	2	100
	500	*1*	*120*
	550	2	156

HARMONIC CONTENT

Recently, an upgrade of GENESIS has been developed that allows for the computation of harmonics in the FEL output for planar undulators [9]. This program has been used to investigate the STARS output at 13.3nm. Fig. 4 shows the results for two radiator segments. To increase the harmonic content of the radiation, a longer duration of the FEL process, i.e. using two radiator segments is profitable. 20% higher peak power and a much cleaner spectrum can be found after the second segment.

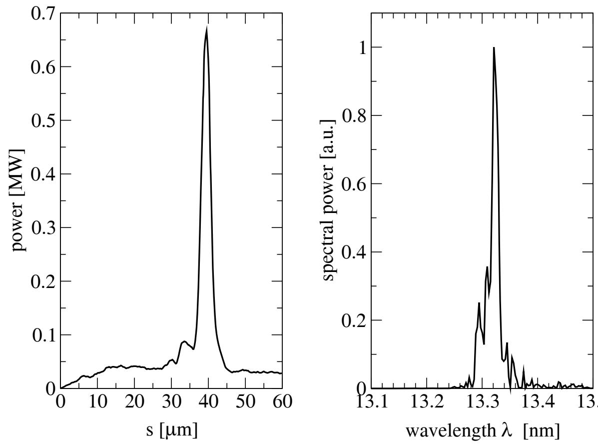

Figure 4: Temporal and spectral power of the 3rd harmonic in the second radiator segment when tuned to 40nm planar radiation.

CONCLUSION

BESSY proposes the construction of a demonstrator, STARS, to investigate the possibility of cascading HGHG stages in order to provide reproducible fs pulses in a wavelength range much shorter than provided by available lasers. The general layout of the undulator section of the machine has been presented, and simulation results of the expected performance of different operational modes have been shown. The proposed layout proved to be flexible enough to cope with a wide range of bunch parameters, due to the modular construction of the radiators and the flexibility provided by the dispersive sections. Calculation with an emittance of 1.5 πmm mrad and an energy spread of $1.0{\cdot}10^{-4}$ predict almost the same peak power as calculations for an emittance of 1.0 πmm mrad and an energy spread of $3.3{\cdot}10^{-5}$, when the undulator section is properly optimized and the second radiator segment is used.

It is known that the synchronization between the bunch and the seeding radiation is one of the critical aspects of HGHG FELs. The effects of timing jitters is expected to be large, but has yet to be studied. The influence of magnetic errors, trajectory offsets and undulator errors will be studied in the near future, but their influence is expected to be far less critical.

REFERENCES

[1] ”The BESSY Soft X-ray Free Electron Laser, Technical Design Report”, March 2004, eds.: D. Krämer, E. Jaeschke, W. Eberhardt, ISBN 3-9809534-0-8, BESSY, BERLIN (2004).

[2] A. Doyuran et al., ”Characterization of a High-Gain Harmonic-Generation Free-Electron Laser at Saturation”, Phys. Rev. Lett. 86, 5902 (2001). URL: http://link.aps.org/abstract/PRL/v86/p5902.

[3] The STARS Design Group, ”STARS - Proposal for the Construction of a Cascaded HGHG FEL”, BESSY Internal Report, Berlin, October 2006.

[4] M. Abo-Bakr et al., ”STARS — A Two-Stage High-Gain Harmonic Generation Demonstrator”, Proc.of thr Particle Accelerator Conference (PAC 2007), Albuquerque, New Mexico.

[5] J. Knobloch et al., ”STARS — An FEL to demonstrate Cascaded High Gain Harmonic Generation”, FEL’07, this proc.

[6] S. Reiche, ”GENESIS 1.3: A Full 3D Time Dependent FEL Simulation Code”, Nuclear Instruments and Methods A429 (1999) p. 243.

[7] J. Bahrdt, W. Frentrup, A. Gaupp, B. Kuske, M. Meseck, M. Scheer, ”Undulators for the BESSY Soft X-ray Free Electron Laser”, Proc. of the 26th International Free Electron Laser Conference (FEL 2004) Trieste, Italy.

[8] L. Giannessi, S. Spampinati and P. Musumeci, ”Non Linear Pulse Evolution in Seeded and Cascaded FELs”, Proc. of the 27th International Free Electron Laser Conference (FEL 2005), Stanford, California, USA.

[9] S. Reiche, K. Goldammer, P. Musumeci, “Recent Upgrade to the Free-electron Laser Code Genesis 1.3,”, Proc.of thr Particle Accelerator Conference (PAC 2007), Albuquerque, New Mexico.