THE BESSY SOFT X-RAY FEL USER FACILITY*

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Abstract

Free Electron Lasers will be the future light sources to generate intense ultra-short photon pulses. The user requests for an optimized 2nd generation FEL facility in the VUV to soft X-ray range demands for ultra short photon pulses (Δt • 20 fs) at a peak power of several GW. Achieving a high shot to shot reproducibility of the pulse shape and pulse power will be mandatory and is feasible in a seeded High Gain Harmonic Generation (HGHG) approach.

Freely selectable photon polarization and wavelength tuning is essential for the new light sources as the proposed BESSY-Soft X-ray FEL user facility. Variable pulse repetition rates and alterable pulse patterns, including fast switching of the full bunch train or single bunches to different parallel operating FEL-Lines thus are foreseen for the facility.

BESSY's recently published Technical Design Report for a multi-user facility[1] is based on a cascaded HGHG-scheme[2]. The combination of a superconducting CW linac, based on the TESLA-development, and the stability and reproducibility of the HGHG-scheme together with frequency and polarization tuning using gap-variable APPLE III-type undulators are the key elements for the proposal presently under evaluation by the funding agency. The status of the BESSY HGHG-FEL project is reviewed in the paper.

INTRODUCTION

Since 1999 BESSY is operating a 3rd generation light source, BESSY II, serving for experiments in the VUV to soft X-ray range; for metrology application a new source, optimized for the EUV spectral regime, the Metrology Light source (MLS) is under construction[3]. As femto-second time-resolved experiments are of increasing interest[4], a femto-slicing X-ray source was commissioned recently at the BESSY storage ring[5]. Though the sub-100 fs pulses are more than 2 orders in magnitude shorter than typical storage ring photon pulses, the low intensities achievable sets practical limits with this kind of source.

BESSY therefore presented the Technical Design Report for a multi-FEL, multi-user facility in the photon energy range 24 eV to 1000 eV, utilizing three independent cascades of HGHG-FEL to frequency convert an fs-seed pulse from an external UV laser to shorter wavelength. This technique assures reproducible radiation pulses controllable down to a few femtoseconds in duration. Further advantage of this approach is the external seed serving as master clock for the synchronization of pump-probe experiments over the hole wavelength range from the UV to soft X-rays.

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Table 1 lists some of the main performance parameters of the BESSY soft X-ray FEL. In combination with a superconducting electron-linac a unique flexible light source will be available able to adapt to any experimental requirement in terms of pulse repetition rate and pulse pattern.

Table 1: Parameters of the BESSY Soft X-ray FEL.

Parameter	Value	Unit
No. of FEL lines	3	
No. of end stations	9 (15)	
Wavelength range	51 – 1.24	nm
Beam peak power	1.5 - 14	GW
Peak brilliance	$6 \cdot 10^{29}$ - $1 \cdot 10^{31}$	$ph/s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%bw$
Pulse duration	20	fs
Min. pulse separation	2	μs
Repetition rate	1 - 25	kHz
Photon beam size	14 - 160	μm
Beam divergence	37 - 140	μrad
Electron energy	2.3	GeV
Operation mode	CW	

THE FEL FACILITY

The FEL facility will be located in close neighbourhood to the BESSY laboratory making effective use of synergies in machine and experiment developments. Fig. 1 gives an architectural view of the future complex.

Fig. 1: Aerial view of the proposed BESSY complex with the BESSY II light source circular building, the MLS at right hand and the 450 m long FEL-building housing linac, the FEL-lines and experimental areas.

Simulation of Photon Beam Characteristics

Based on start to end simulations using the codes ASTRA and ELEGANT electron beam phase space distributions were derived and the 3-D FEL-code GENESIS[6] was used in time-dependent mode to calculate the FEL-output pulse and pulse spectral density. Fig. 2 shows a typical result at the last undulator (amplifier) exit of the third cascade of the so-called 'medium energy' FEL spanning photon energies 100 to 600 eV. A17 fs (fwhm) Gaussian profile pulse of 500 MW peak power at λ=258 nm was assumed for seeding the first HGHG-stage.

The output pulse duration reflects the (in principle variable) seed duration while the relative spectral linewidth is about $1\cdot10^{-3}$ with two asymmetrically distributed sidebands. The sidebands are originated by overbunched electrons performing synchrotron oscillations in the ponderomotive bucket. The number of sidebands scales with the number of HGHG-stages of the cascade while the asymmetry is caused by the slippage.

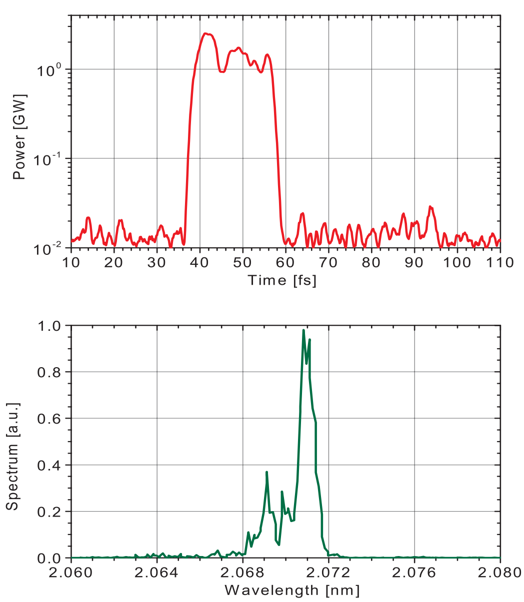

Figure 2: Typical pulse structure (upper graph) and spectral density (lower graph) as calculated for the medium energy FEL line, at λ_{ph}= 2 nm.

Shot noise in the undulators is expected to cause degradation of the coherent properties of the HGHG output especially when operating at very high harmonics as is the case of cascading. The ratio of noise power P_n to signal power P_s at the input (in) and output (out) satisfies the relation

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

where n is the harmonic number. For the BESSY-FEL n = 225 at maximum as the seed laser's wavelength is 280 nm and the shortest output wavelength λ = 1.24 nm. To reproduce the coherence of optical seed pulse at the high power output despite of the high n, a peak-power of the optical seed in the order of 500 MW is required.

Calculation for an output wavelength of 1.24 nm varying the seed-pulse power from 150 W to 150 MW in steps of a factor of 10 clearly show the effect of the shotnoise, see fig. 3. Vanishing influence of the noise can be expected only at the highest seed power. A reasonable output signal of 100 MW is achieved for a seed of 1.5 MW peak power, while saturation (2 GW output) requires a seed in excess of 150 MW. Simulations are based on the BESSY HE-FEL geometry.

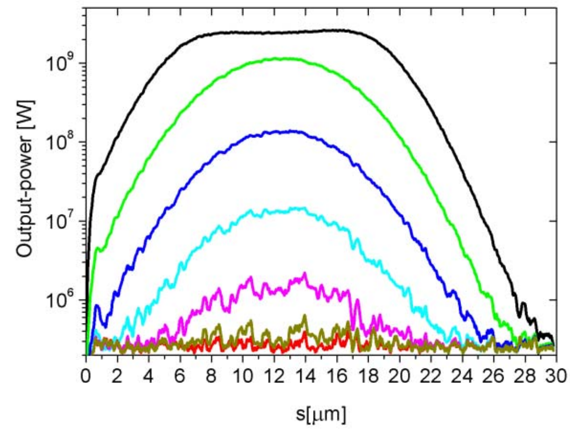

Figure 3: Output pulse power along the electron bunch position at the exit of a 15 m long undulator for different input seed power. The graphs correspond to a seed power of P_s = 150 MW (upper black line) successively reduced by a factor of 10 down to 150 W (lowest red curve).

TESLA Modules for the CW-Linac

Basis for the linac accelerating sections are TESLA 9-cell cavities with eight cavities arranged in a common cryo-module. Minor modification are required to allow for CW-operation of the modules. As a modest accelerating field of 16 MV/m will be used the cryogenic losses are less than 25 W/cavity permitting to run the cavities CW without exceeding the level of capacity of 1.8 K superfluid He of 3.6 kW. CW operation mode gives full flexibility to set the machine according to the experimenters needs rather than to provide a fixed pulse pattern at constant repetition rate.

Work at the RF test bench is proceeding. A first 15 kW klystron amplifier has been developed and is in routine operation for tests at cavities, tuners and couplers; a 10 kW prototype 1.3 GHz IOT power-amplifier will be available by mid of the year.

The Photoinjector

The electron beam parameters are of major impact to the FEL characteristics, as the beam emittance has to be smaller than the photon output wavelength λ_{ph} to achieve lasing:

$$\frac{\varepsilon_o}{\gamma} \le \frac{\lambda_{ph}}{4\pi}$$

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where ε_o is the normalized emittance and $E/m_e c^2 = \gamma$ with the electron beam energy E and the electron rest mass m_e.

The PITZ RF-photoinjector[7] now in operation at the DESY VUVFEL already demonstrated the performance as required for the BESSY-FEL injector. However, as the repetition frequency of this injector is 10 Hz, an improved version of the gun cavity was designed to allow for short bunch-trains (3 bunches spaced by 2 – 3 μs) at a repetition frequency of up to 1 kHz. This gun will be tested at PITZ.

Recent progress in superconducting RF-injector development stimulated a FZR-BESSY-MBI-DESY collaboration to construct a superconducting 3.5-cell RF-injector[8]. Simulations indicate that with RF-focussing a 1 mm·mrad slice emittance can be expected when a long flattop photocathode laser profile is adopted with most realistic rise and fall-times of 4 ps. Similar results were obtained in simulations utilizing the emittance conservation principle.

R&D at the HoBiCaT-Test Bench

The HoBiCaT test bench now operational at BESSY is designed to qualify linac components. Feed by a Linde TCF50 LHe refrigerator and equipped with a pumping station providing a cooling capacity of 80W at 1.8 K.

Fig. 4 shows a photograph of the bench together with one out of two recently delivered 9-cell cavities manufactured and processed entirely by industry[9]. The cavities exceed the specifications required for the BESSY-CW linac structures in terms of maximum field and unloaded Q-value.

Power tests with the TTF-III coupler confirmed limitations in CW operation at 10 kW travelling-wave (TW) and 5 kW standing-wave (SW) power. Minor modifications improving cooling of the inner conductor indicated that the coupler will operate safely up to 8 kW SW and suggest that even 25 kW SW power should be feasible[10].

As the BESSY low current accelerating structures are dominated by microphonics effective Piezo-dampers, presently under preparation, are needed to reduce RF-power and thus costs for RF-systems and cryo-infrastructure.

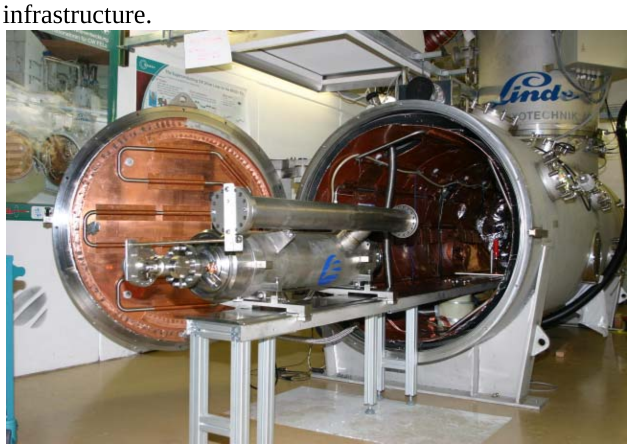

Figure 4: Photograph of the first TESLA type 9-cell cavity produced by industry at the HoBiCaT test bench.

FEL Undulator Sections

For the FEL-undulator sections various types of insertions (linear and elliptical permanent magnet devices) of different period-length are required. All undulators sum up to a total length of 120 m for the three FEL-lines. The undulators are segmented with a maximum length of 4 m. For wavelength tuning all undulators are variable in gap-setting. Photon beam polarization is controlled by row-shifts of modified APPLE II permanent magnet IDs to be used as the radiator and the final amplifier in the last HGHG-stage. The design strategies following closely the successful operating IDs at BESSY II[11].

SUMMARY

The technical design of the BESSY soft X-ray FEL facility shows that the project can be realized with existing technologies. R&D in the most challenging injector and linac hardware is progressing. Evaluation of the project is scheduled for mid 2005.

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