OF THE BESSY SOFT X-RAY FEL USER FACILITY*

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Abstract

The user request for an optimized 2nd generation FEL facility in the VUV to soft X-ray range demands for reproducible ultra short photon pulses at an energy level of mJ/pulse. Tunable wavelength and variable beam polarization as well as synchronization to external lasers are essential in future time-resolved pump-probe experiments. These features can be met best in a seeded HGHG approach. Free selectable pulse repetition rates and pulse pattern in combination with more than one FEL-line operating in parallel are features achievable with a RF photoinjector in combination with a CW superconducting linac. Following these ideas the technical design for a soft X-ray FEL user facility for the VUV to soft X-ray range, i.e. 51 to 1.24 nm photon wavelength. The Technical Design Report for the BESSY Soft X-ray FEL based on a multi-staged HGHG scheme was issued recently [1].

INTRODUCTION

Ultra-short pulses from free electron lasers are *the* tool in future time-resolved fs-physics experiments. Spatial and temporal coherence and intrinsic stable photon beam are mandatory for a future multi-user FEL facility. The cascaded High-Gain-Harmonic-Generation (HGHG)-FEL scheme as pioneered by BNL, ref. [2], is the most promising scheme in achieving high performance fs-photon pulses as the properties of the FEL-output reflects the high-quality characteristics of the optical fs-seed pulse. The result is a photon pulse of selectable short duration, a high degree of reproducibility of the pulse form and pulse energy and stability and control on the central wavelength and bandwidth. The design of a FEL-user facility with three FEL-lines operating in parallel, spanning the photon energies 24 – 120, 100 – 600 and 500 – 1000 eV, delivering pulses of ≤ 20 fs (fwhm) at variable beam polarization has been worked out.

A 2.3 GeV CW-linac driving the FEL process together with a flexible injector will allow full control on the pulse repetition rates and pulse pattern. Time dependent simulations using GENESIS 1.3, ref. [3], have been performed using a start to end approach [4].

The performance of the BESSY-FEL in terms of peak brilliance and peak power is displayed in Fig. 1. For comparison the data for the DESY VUV-FEL, the European XFEL and LCLS are plotted. Comparing the FEL performance parameters to 3rd generation light sources as BESSY II, a gain can been seen of more than 10 orders in magnitude.

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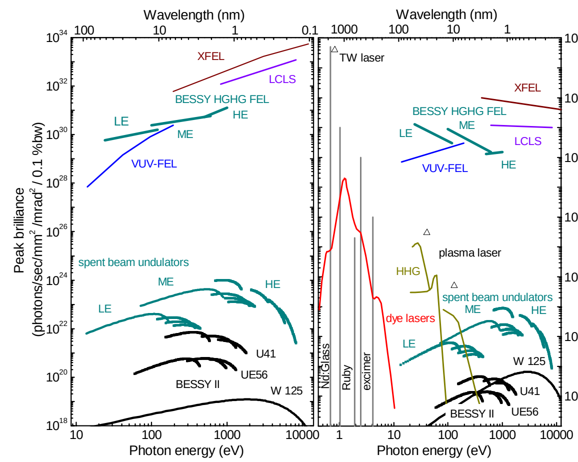

Figure 1: Peak brilliance and peak power from the BESSY-FEL compared to the BESSY II storage ring based light source, the DESY VUV-FEL, the European X-FEL and SLAC's LCLS.

THE BESSY SOFT X-RAY USER FACILITY

The BESSY-FEL utilizes a 2.3 GeV CW-superconducting linac fed by a 1 kHz RF-photoinjector. Two bunch compressors operating at beam energies of ~220 and ~750 MeV compress the 45 ps long, 65 A pulse from the gun to a useful bunchlength of ~ 1 ps at 1.8 kA peak current at the entrance to the undulators sections. Extraction is accomplished at 1.0 GeV and at full energy. From the train of three bunches as generated in the injector a single bunch is kicked into each of the 3 FEL-lines optimized for 51 – 10, 12 – 2 and 2.5 – 1.24 nm photon wavelength. Thus all three FELs are running in parallel at a repetition frequency of up to 1 kHz.

The FEL-lines consist out of a cascade of HGHG-FELs. The interaction of a short fraction of the electron bunch with the optical field of a tunable fs-seed laser (230 < λ_{seed} < 460 nm) leads to an energy modulation in the first short undulator (modulator). This modulation is converted into spatial bunching in the following dispersive section, which includes bunching on higher harmonics of the seed frequency. Thus the second undulator (radiator), when tuned to the n-th harmonic of the seed frequency (n typically 3 or 5) radiates coherently at the chosen harmonic wavelength. Using this radiation as seed for the next stage allows to reach wavelength ~ 1 nm within 4 stages. The last element of the chain is a long undulator, the "final amplifier", which is seeded on the

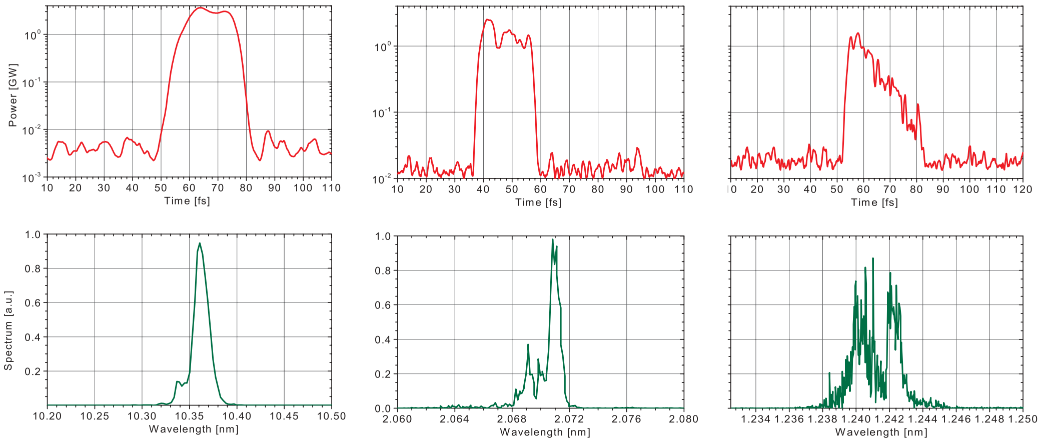

Figure 2: Simulation results for the cascaded BESSY HGHG-FEL-lines. Upper graphs time resolved power distributions, Lower graphs spectral power distributions. Data correspond to the high energy end of the 2 to 4 fold staged FEL-lines, corresponding to a wavelength of 10.3, 2.0 and 1.24 nm. In all cases a 17 fs (rms) Gaussian seed pulse of 500 MW peak power was assumed.

fundamental of the desired wavelength, the undulators-length optimized to saturate the amplification process.

FEL Output Simulations

Detailed time-dependend simulation on the interaction of the electrons and the radiation field along the undulators and dispersive section have been performed with the 3-D simulation code GENESIS, modified to allow for seeding and proper treatment of the higher harmonics.

Power optimized simulation results on the time resolved power distribution and corresponding spectral power distribution are depicted in figure 2 for the 3 BESSY-FEL-lines [1, 5].

As expected the FEL output is determined by the external seed laser field. A stable clear spectrum results, the radiation pulse is transversely and longitudinal highly coherent with a smooth temporal pulse shape. This is the result of the high power seed which is dominating the statistical shot noise.

The RF-Photoinjector

Operation of the BESSY-FEL requires production of bunch trains containing 3 single bunches at a 1 kHz repetition frequency. The spacing of bunches within the train is 3 µs a compromise between duty cycle of the room-temperature gun cavity and the demands on the linac RF-system with respect to beam loading. To generate the electron bunches at a charge of 2.5 nC an RF photoinjector based on the PITZ design [6] is intended to be used. Calculations show that with a short rise and decay time of a “flat-top” intensity profile photocathode laser a normalized slice emittance of less than 1.5 π·mm·mrad can be achieved [7]. Thus the PITZ-type photogun modified to higher repetition rates will be the technical starting point for the BESSY-FEL.

However, a superconducting RF-gun, as is presently under construction by a FZR-BESSY-MBI-DESY consortium, will replace the injector later on.

TESLA Modules for the CW-Linac

The superconducting acceleration structures are based on the TESLA linear collider modules that have demonstrated reliable operation at TTF [8]. The TESLA modules consist of eight niobium 9-cell cavities, each modules being 12 m long. 18 modules are needed for the 220 m long 2.3 GeV linac. The operation field of ~16 MV/m CW is the economical optimum with respect to investments and long-term operation costs. Minor modifications are required to adapt the (pulsed) TESLA technology for CW. Thus the increased He-flux from the cavities (20.5 W/cavity) requires a modest enlargement of the two-phase He supply line.

The HoBiCaT Teststand

To confirm the basis for a reliable CW operation an detailed qualification program started at BESSY. Test of couplers and tuners, optimization of cryogenic parameters as bath temperature etc. are performed. For this purpose a Horizontal Bi-Cavity Test facility (HoBiCaT) has been set up [9], see also figure 3.

Figure 3: Photo of the BESSY HoBiCaT test bench

Tests of new concepts of damping microphonics - most important in CW operation - are under preparation. The test bench also will serve in the RF source R&D, allowing for a cost-optimized specification for the 144 1.3 GHz-power sources.

Commissioning of the bench is in progress, 1.8 K LHe is provided from an existing Linde TCF50 cryogenic plant connected to a pumping station.

Two 9-cell cavities entirely manufactured and processed by industry are available now for testing.

The Undulator-Sections

For the three FEL-lines in total 120 m of undulators of different period lengths is needed to ensure a proper matching between modulator and radiator of the various stages, ranging from λ_u = 122 mm to 28.5 mm. A minimum gap of 10 mm, is sufficient to cover the full wavelength range. In each case the undulators are variable gap devices, the radiators of the last HGHG-stage and the final amplifier undulators will follow the elliptical permanent magnet design now known as APPLE III [10].

The radiators and final amplifiers will be built up from segmented undulators of typically 3.5 m in length. These segments are spaced by 0.95 m long intersections equipped with phase shifters, focusing quadrupole magnets, steering elements, vacuum pumps and a variety of diagnostic elements as OTR, wire scanner, beam position monitors etc. for beam characterization and manipulation.

Special attention has been paid to the undulators vacuum chamber to avoid beam degradation due to wakefields. An all Cu-vacuum chamber with a beam duct of surface roughness < 100 nm rms is presently favored in the design.

Beamlines

The three FELs will be equipped with three beamlines each: optimized for high resolution experiments, a “white light” beamline without any monochromatization and a high intensity station conserving the short pulse structure of the FEL beam. Table 1 gives main parameters for the high-energy (HE) FEL beamlines as an example. Data were calculated from detailed ray tracing [1].

Table 1: Main parameters for the HE-FEL beamlines.

Beamline	Bandwidth (meV)	Pulse length (fs)	Pulse energy (nJ)	Energy density (mJ/cm^2)
High resolution	20 - 33	650 – 120	2.4 – 10	0.23 – 1.4
White light	2000	10	11000	120000
Short pulse	800	11	600	250
FEL output	2000	10	15000	1000

CONCLUSIONS AND OUTLOOK

The seeded soft X-ray FEL facility ideally will complement the 3rd generation synchrotron light source BESSY II. The new machine is based on existing technology making use of hardware developed for high energy physics collider and/or hard X-ray FELs. Options as seeding with future intense short-wavelength HHG lasers (λ ~ 30 nm)[11] as well as expanding the number of FEL-lines from 3 to 5 have been incorporated to the design of the BESSY Soft X-ray FEL.

The flexibility of a CW-accelerator together with widely used features as continuous wavelength tuning, variable beam polarization, and taking advantage of the specific characteristic of seeded FELs as transverse and longitudinal coherence in combination with ultra-short pulses at highest peak brilliance, open-up the field of ultra-fast time resolved spectroscopy in the VUV to soft X-ray spectral range.

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