THE BESSY 2nd-GENERATION SOFT X-RAY FEL USER FACILITY*

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Abstract

VUV-to-soft-X-ray FEL facilities promise to open fundamentally new frontiers for the synchrotron user community. So-called 2nd generation FELs, which use seeded schemes rather than SASE, an deliver reproducible ultra-short photon pulses in the GW range. BESSY has been designing a high-gain-harmonic-generation (HGHG) based FEL with a 2.3 GeV CW superconducting driver linac that covers photon energies from 24 eV to 1 keV. The design presented here provides full tuneability of photon energy, variable beam polarization and complete synchronization to external lasers—all essential for future femtosecond, time-resolved pump-probe experiments. In addition, CW operation offers the flexibility to tune the repetition rate and pulse pattern to the users' needs.

DESCRIPTION OF THE FACILITY

The BESSY Soft X-Ray FEL (BESSY FEL) is a multi-user facility with 9 beam lines (later 15) spanning the energy ranges 24–120 eV, 100–600 eV and 500–1000 eV with three independed FELs. These provide fully transverse and longitudinal coherent, diffraction limited radiation with complete polarization control and pulse lengths in the 20 fs range [1].

A cascaded HGHG scheme was adopted for the FELs [1], whereby a tunable Ti:Sa femtosecond laser is used to energy modulate the electron beam in a short undulator (modulator). A dispersive chicane converts this to a spatial modulation with higher-harmonic content. A second undulator, tuned to a harmonic then generates coherent radiation that seeds the next HGHG stage. The cascade is repeated until the desired wavelength (down to 1.25 nm) is reached. In the end, a longer final amplifier undulator drives the radiation field into saturation. Delay lines between HGHG stages ensure that always a fresh portion of the bunch is used for seeding to maximize the radiation quality (fresh-bunch technique [2]). A strength of the HGHG scheme is that the output radiation is essentially determined by the properties of the seed laser, yielding reproducible "clean" pulses both temporally and spectrally. Furthermore the system is "self-synchronizing", simplifying pump probe experiements.

Table 1 lists the main parameters of the BESSY FEL. An electron-beam energy of 2.3 GeV with an emittance of order 1.5 π mm mrad (sliced) and a peak current of 1.8 kA is needed for the high- and medium-energy FELs. The low-energy FEL will operate at 1 GeV. The overall layout of the BESSY FEL facility is shown in Figure 1.

Table 1: Main parameters of the BESSY FEL.

Parameter	Value
No. of FELs	3
No. of beamlines	9 (later 15)
Photon energy	24–1000 eV
Photon peak power	1.5–14 GW
Pulse duration	< 20 fs
Repetition rate	1 kHz (later 25)
Peak brilliance	6×10^{29}–1.3×10^{31}
Beam energy	2.3 GeV
Peak current	1.8 kA
Bunch charge	2.5 nC
Emittance (slice)	1.5 π mm mrad

Beam acceleration is provided by a superconducting CW linac, fed by a normal-conducting photoinjector running at a high-repetition rate of 1 kHz. Since every macropulse will have three microbunches to be distributed by fast kickers among the three FELs, each FEL will run at 1 kHz, a rate well matched to laser systems used for pump-probe experiments. An upgrade to a fully CW superconducting injector (25 kHz bunch rate), is planned for additional flexibility in pulse repetition rates and bunch patterns.

S-bend chicanes at 219 MeV and 753 MeV are used for two stage bunch compression [1] of the approx. 65 A bunch current out of the gun (29 ps FWHM bunch length) to the 1.8 kA(1 ps bunch length) peak current required for the HGHG scheme. These bunch compressors require off-crest beam acceleration to imprint an energy chirp on the beam. A 3rd harmonic section consisting of eight 9-cell cavities, as in [3] will be used to linearize the energy chirp.

THE DRIVER LINAC

The photoinjector

The initial photoinjector is based on the design developed by the PITZ collaboration, of which BESSY is an active member. So far, measurements with the PITZ gun have achieved a *projected* emittance of 1.7 π mm mrad at 1 nC [4]. Here, a flat-top laser profile with 4 ps rise time was used. Simulations have been performed for the BESSY-FEL laser systems (4 ps rise time, 38 ps flat top) which demonstrate that an average slice emittance of 1.5 π mm mrad can be achieved at 2.5 nC bunch charge [5].

For 1 kHz operation, the BESSY-FEL gun has improved cooling to handle 75 kW of power dissipation. A fast amplitude control loop may be used to reduce the fill and decay times of the cavity and hence the power requirements

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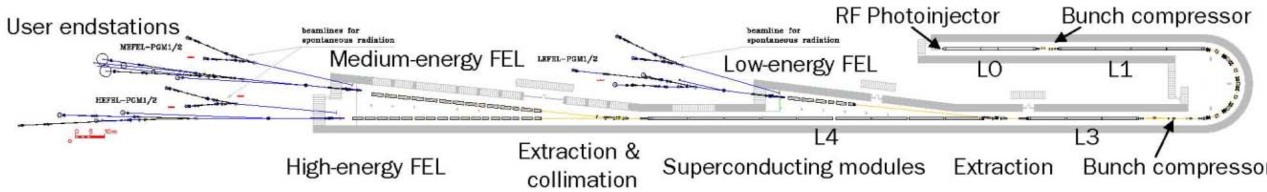


Figure 1: Layout of the main components of the BESSY FEL.

too. Recent tests of BESSY's high-duty factor prototype gun at PITZ have demonstrated stable cavity operation up to 47 kW and 51 MV/m, limited by the available power [6].

Tolerance studies have shown that field control in the injector cavity is critical for beam jitter control in the FELs. Hence the RF gun incorporates a field pickup probe to improve the RF field control. So far, the power tests demonstrated that heating at the pickup will not be an issue.

The superconducting linac

TESLA-type superconducting modules will be used for acceleration in the main linac. 18 eight-cavity modules for a total of 144 cavities are required. The operating field is of order 16 MV/m at a Q_0 of 1.3×10^{10} which lies well within the range achieved at the VUV-FEL. Even if a cavity fails, the remaining seven in the module can provide the full energy while operating below 20 MV/m.

To adapt the pulsed TESLA technology for CW operation, the HOBICAT facility for superconducting cavity units has been operational at BESSY since 2004 as part of the EuroFEL collaboration [7]. The program investigates issues such as module modifications for the relatively high CW heat load (20 W/cavity), thermal loads on the RF coupler system, precise RF field control, and microphonic detuning of the very-narrow-bandwidth cavities. Solutions for these issues have been identified and are being tested in HOBICAT. The facility also serves to train BESSY staff in handling and operating superconducting cavities.

Collimation

Collimators before each FEL protect the radiation sensitive NdFeB undulator structures from missteered beam and dark current, filtering both the longitudinal and transverse phase space [8]. Transverse collimation is achieved by aperture blocks that intercept off-axis particles. Longitudinal collimation is provided by a dispersive dog-leg section that incorporates apertures with a 5% energy acceptance. The design is such that the wakefield and CSR effects on the beam remain small yet the length of the collimator is less than 43 m long. The length includes a matching section and room for beam diagnostics (phase space measurements, current transformers, etc.) and two tune-up dumps.

THE FELS

Altogether, 120 m of undulators are required for the three FELs [9]. So far, BESSY staff have built more than 44 m of undulators for BESSY-II, proving that the prerecuisite in-house expertise for the FEL construction exists. For the BESSY FEL, periods range from 120 mm to 28.5 mm with a minimum gap of 10 mm. Wavelength tuning is achieved by gap changes. All undulators will be planar except for the final radiators and amplifiers, which offer full polarization control by APPLE-III devices. The planar undulators reduce the complexity and cost of the FELs, and simulations confirmed that this does not diminish the photon-beam quality or power. The BESSY-devloped APPLE-III devices have about 1.4 times the on-axis field of APPLE-II devices.

A segmented layout has been adopted, with sections no longer than 3.5 m. 0.95 m gaps between sections accomodate quadrupoles, phase shifters, vacuum pumps and beam diagnostics. A relative alignment accuracy of up to 20 μm (high-energy FEL) is required between segments, which will have to be mounted on remotely controlled stages. The FEL output serves as feedback for alignment optimization.

The relative gap accuracy must be $< 3\ \mu$m for which a new measurement system was developed at BESSY and installed on the UE49 APPLE-II undulator. A gap reproducibility of $\pm 1.5\ \mu$m was demonstrated with this system.

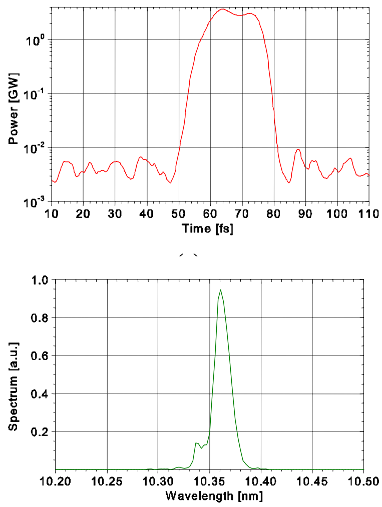
For the frame to handle the strong forces and provide gap reproducibility and to reduce its cost, a new bionically optimized mechanical design has been developed at BESSY. This is currently being tested in the installation of the UE112 undulator (APPLE-II) in BESSY II.

Each FEL will be equipped with three beamlines, for a total of nine. These are optimized for high-resolution (resolving power up to 50,000), white light (no monochromatization), and high intensity that conserves the short pulse lengths. Data were calculated by detailed ray tracing [10]

S2E AND TOLERANCE STUDIES

Performance predictions for a machine such as the BESSY FEL require extensive start-to-end (S2E) simulations from the cathode laser through to the photon beamline. This is further underscored by the fact that tolerance studies are needed not only for stability analyses of the FEL radiation, but also to optimize the hardware layout.

Start-to-end simulations BESSY is able to perform such complete S2E simulations, using `ASTRA` for the injector and booster, `ELEGENT` for the main linac, and `GENESIS` 1.3 for a time-dependent treatment of the seeded HGHG scheme [1]. The radiation is then propagated to the beamline by the



(b)

Figure 2: FEL pulse versus time and wavelength for the low-energy FEL.

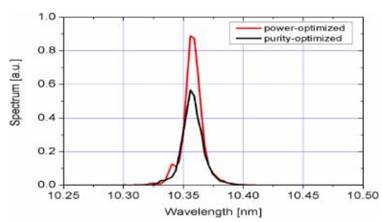


Figure 3: The dispersive sections in the HGHG cascade can be optimized to either yield high-power or high-purity output radiation.

Fourier optics method to characterize the radiation source [11] and enable a proper beamline design.

Figure 2 depicts an example of the radiation expected from the low-energy FEL. The output is determined by the external seed, here a 17 fs, 500 MW pulse. For a clean output, the seed power must be sufficiently high to dominate the shot noise, which is amplified by the square of the harmonic number of each HGHG stage.

Depending on the needs of the users, the dispersive sections can be optimized to provide high-power output or a high spectral purity (see Figure 3) [12]. In the former case, overbunching in the dispersive section results in the sideband of the spectrum in Figure 2(b). A reduction of the dispersion cleans up the spectrum but sacrifices power.

Tolerance studies Extensive tolerance studies have been performed to analyze the stability of the FEL radiation [13, 14]. These involve repeated S2E simulations with anticipated "errors" such as amplitude and phase errors in the cavities and laser-timing errors. Especially in the injector, where the beam is not fully relativistic, energy and time jitter couple and affect the bunch profile. Similarly the dispersive bunch compressors translate an energy jitter into a timing jitter. Moreover, phase errors before the bunch compressors affect the energy-time correlation which in turn impacts the compression (and hence current profile).

The impact of jitter thus is two-fold: First the slice properties of the bunch are modified and hence the quality of the FEL-radiation. Second, because of timing jitter the seed laser "samples" different parts of the bunch (with different properties) from shot to shot.

The studies have shown that the layout of the FELs can be optimized to reduce the impact of the beam jitter on the photon radiation. For example, the HGHG process is reasonably insensitive to variations in the beam energy—it is, in a sense, self-stabilizing. This can be used to reduce the impact of timing jitter on the output power by tuning the undulators' K parameter to a beam energy slightly below the true beam energy. Also, increasing the length of the radiators reduces the jitter of the output radiation. Thus, configurations have been identified that reduce the ouput-power sensitivity to beam jitter by about 50%.

CURRENT STATUS

Following publication of the scientific case for the BESSY FEL in the "Visions of Science" and the subsequent release of the Technical Design Report in 2004, the German Wissenschaftsrat (Science Council) evaluated the BESSY-FEL proposal in 2005. The conclusions were made public in May 2006, giving the proposal very high marks. The Wissenschaftsrat agreed, that BESSY has the full technical know-how for construction of the BESSY FEL and that all critical components are being addressed in the current R&D program. Moreover, the major components of the BESSY FEL, such as linac modules, RF system and refrigeration have been designed for conservative and robust user operation with parameters well within the range that can be achieved with the present state-of-the-art. As underscored by the Wissenschaftsrat, the demonstration of HGHG and the development of the superconducting injector remains a high priority. Both of these are being addressed in Euro-FEL and SRF-Gun collaborations, and options to expand on these experiments are being investigated.

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