STARS—AN FEL TO DEMONSTRATE CASCADED HIGH-GAIN HARMONIC GENERATION*

M. Abo-Bakr, W. Anders, J. Bahrdt, K. Bürkmann, P. Budz, O. Dressler, H. Dürr, V. Dürr,
W. Eberhardt, S. Eisebitt, J. Feikes, R. Follath, A. Gaupp, R. Görgen, K. Goldammer,
S. Hessler, K. Holldack, E. Jaeschke, T. Kamps, J. Knobloch†, O. Kugeler, B. Kuske,
P. Kuske, D. Krämer‡, F. Marhauser§, A. Meseck, R. Mitzner¶, R. Müller, A. Neumann, M. Neeb,
K. Ott, D. Pflückhahn, T. Quast, M. Scheer, T. Schroeter, F. Senf, G. Wüstefeld
BESSY, Albert-Einstein-Strasse 15, 12489 Berlin, Germany

Abstract

BESSY is proposing a new facility to demonstrate the cascading of two high-gain harmonic-generation stages for the generation of FEL radiation. This facility, called STARS, is planned for lasing in the wavelength range 40 nm to 70 nm. A 325-MeV CW driver linac provides a peak current of 500 A at a bunch charge of 1 nC. The linac consists of a normal-conducting gun, three superconducting TESLA-type modules modified for CW operation, a third-harmonic unit to linearize the RF potential and a single-stage bunch compressor. This paper discusses the facility layout and the main operating parameters.

MOTIVATION

Femtosecond pulses from linac-based free-electron lasers are unique tools for future time-resolved experiments. In March 2004, BESSY published the TDR for a free-electron laser user facility that covers the VUV to soft X-ray range (BESSY FEL) [1]. This second-generation FEL facility is seeded and uses the high-gain harmonic generation (HGHG) [2] scheme to produce coherent radiation down to the 1-nm range. This scheme offers the possibility to generate photon pulses of variable femtosecond duration, gigawatt peak power, full shot-to-shot pulse reproducibility, wide-range tunability and full transverse and longitudinal coherence. To reach the highest energies, HGHG cascades with up to four stages must be employed.

Following the evaluation of the TDR in 2005/06 by the German Science Council, it was recommended that the BESSY FEL be realized on condition that its enabling technology, the HGHG *cascade*, be demonstrated beforehand.

To address this important issue, BESSY is therefore proposing to build a two-stage HGHG cascade with a superconducting driver linac called STARS (Superconducting Test Accelerator for Radiation by Seeding) [3, 4]. Although its primary purpose is to validate the cascading of HGHG stages, many components and technical issues are nearly identical to those of the BESSY FEL. Hence, STARS serves as an ideal test bed for operating CW superconducting technology, diagnostics, synchronization, and for studying beam generation, manipulation and transport.

To demonstrate the capabilities and potential of seeded, ultra-short-pulse FEL radiation, prototype user experiments will also be installed at STARS. The location of STARS is planned such that it will remain operational even after construction of the BESSY FEL. By expanding the experiments, STARS will therefore migrate towards a full user facility to enhance the BESSY FEL and to enable the exploration of new techniques before they are adopted for the BESSY FEL.

OVERVIEW

STARS will be located on the same site as BESSY-II in Berlin-Adlershof, making use of some of the existing infrastructure while leaving room for the BESSY FEL facility to be built later. The philosophy behind the layout of STARS, as depicted in Figure 1, is to adopt a conservative configuration that provides for "safe" operation in view of the main goal of demonstrating the cascading of HGHG at 70 nm. Hence, components for the driver linac and system parameters were adopted which have already been demonstrated experimentally elsewhere. Nevertheless, "optional upgrades" of the linac are included, some from the outset, that will enhance the FEL's performance to make STARS attractive for future user experiments.

A normal-conducting photoinjector generates high-brightness electron bunches. Three superconducting TESLA-type cryomodules, modified for CW operation, then boost the energy up to 325–380 MeV.[1] The cryomodules contain twenty 9-cell TESLA-type cavities with the possibility to add four further ones at a later date. Bunch compression is achieved in a magnetic chicane following the second module. A collimator and diagnostic beam line preceed the HGHG cascade, permitting linac commissioning before the beam is injected into the FEL section consisting of two HGHG stages and a fresh bunch chicane.

For bunch compression, off-crest acceleration is required. Non-linearities in the longitudinal bunch profile introduced by the RF potential result in a strongly peaked current distribution after compression. STARS thus in-

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† knobloch@bessy.de
‡ now at GSI, Darmstadt
§ now at Jefferson Lab, Newport News
¶ Universität Münster

[1] The final energy depends on whether the third-harmonic cavities, discussed later, are in operation or not.

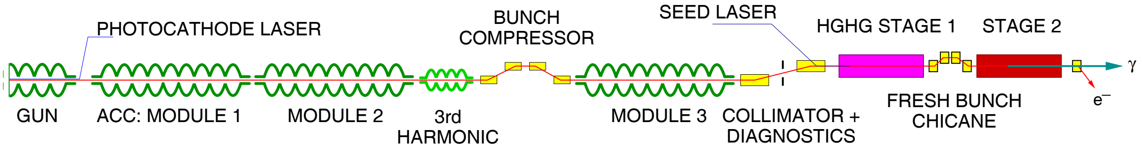

Figure 1: Layout of the main components of STARS.

cludes a third-harmonic cavity system directly after the second module to remove the non-linearities. However, the demonstration of cascaded HGHG is also possible without the linearizing cavities installed, albeit at longer wavelengths and lower power.

ELECTRON-BEAM GENERATION

The electron beam current is generated in an RF photoinjector. Here a modified PITZ normal-conducting system has been adopted [5], primarily because the required beam paramters (slice emittance = 1.5 π mm mrad at 1 nC) have already been demonstrated [6, 7]. A UV photocathode laser illuminates a Cs_2Te cathode with flat-top laser pulses of 20 ps width to release electron bunches of 1 nC charge.

The repetition rate of the STARS injector is a conservative 100 Hz with a pulse length of 25 μs. This is sufficient to demonstrate cascaded HGHG, while operating the gun cavity at a moderate thermal load of 7.5 kW. Stable gun operation, critical to guaranteeing a jitter-free beam, is thus much simpler than for high thermal pulsed loads. An RF pickup is included in the gun-body design to further enhance the control of the RF field. First experiments at low power have demonstrated that the required phase and amplitude stability of 0.3° and 0.1% can readily be achieved and even improved upon [8].

In future, an upgrade to the full 1-kHz operation, as for the BESSY FEL, is planned and the thermal loading will increase to 75 kW. To handle this, the cooling of the PITZ3 gun cavity design was improved and a prototype of the new design was tested successfully to 47 kW power dissipation, limited only by available RF power at the gun [5].

BEAM ACCELERATION

Superconducting RF technology developed by the TESLA collaboration and as described in the BESSY FEL TDR [1] has been chosen for the driver linac of STARS. Although TESLA was originally designed for pulsed operation, both STARS and the BESSY FEL will operate CW for a number of compelling reasons. These include the flexibility to choose bunch patterns more freely and the enhanced RF stability because the RF is alway on. The latter is especially critical to provide jitter-free electron bunches to the HGHG cascade to ensure maximal output and synchronization capabilities for user experiments.

To study the CW operation of TESLA technology, BESSY has already started an intensive R&D program. The Horizontal Bi-Cavity Test facility (HOBICAT) [9] has been set up for this purpose.

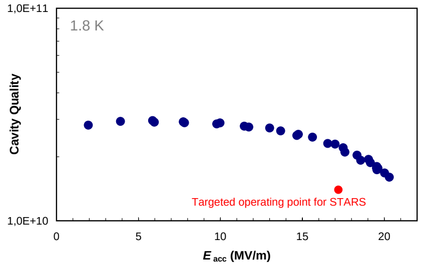

Figure 2: Cavity quality of a CW operated TESLA cavity with all ancillary components (coupler, tuner, HOM pickups, etc.) as measured in the HoBiCaT facility.

Tests of RF couplers [10] and tuners [11] as well as studies such as the optimum bath temperature required for reliable and economic CW operation, have been performed.

Simulations of the HGHG scheme have shown that a beam energy of 325 MeV is sufficient for lasing at wavelengths down to 40 nm. This energy can be reached with three TESLA-type modules containing a total of 20 cavities operating at a moderate 17.2 MV/m. Note that this value takes into account a total decelerating voltage of about 30 MeV in the third-harmonic section. Measurements in HOBICAT have already demonstrated that CW operation at this field is possible while exceeding the STARS design quality factor of 1.4×10^{10} by 65% (see Figure 2).

At 1 nC bunch charge and a repetition rate of 100 Hz, beam loading in STARS is less than 2 W per cavity. Hence, RF power will be needed primarily to compensate the microphonic detuning in the cavities. Microphonic detuning is also a significant contributor to RF instability and thus should be kept to a minimum.

Measurements in HOBICAT have shown that the RMS microphonics are of the order of 3 Hz or less with peak excursions around 15 Hz. A significant portion of these microphonics are at frequencies below 1 Hz and are caused by pressure fluctuations in the helium gas-return system, of order 0.03 mbar RMS [12].

It is expected that the larger volume of the STARS helium system will reduce the level of microphonic detuning. Still, it has already been demonstrated that the detuning can also be compensated with a fast, piezo-based cavity tuner to levels below 1 Hz RMS. Even high frequency components at mechanical resonances have been compensated with this system (see Figure 3).

To provide for an ample safety factor, the RF system will be dimensioned to handle microphonic detuning values of 5 Hz RMS and 25 Hz peak. The optimal bandwidth is 50 Hz, or an external coupling of 2.6×10^7. At 17.2 MV/m accelerating field this translates into an RF power requirement of $P_{\mathrm{ave}} = 3.1$ kW and $P_{\mathrm{peak}} = 5.9$ kW, which the

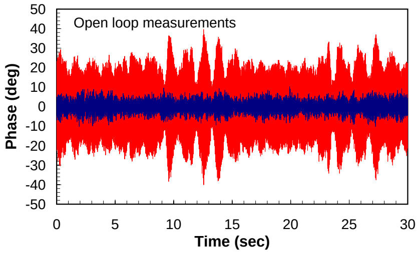

Figure 3: *Open-loop* measurements of the cavity phase stability. The dominant noise source is microphonic detuning resulting in a phase stability of 14.9° RMS (red curve). When detuning compensation is activated with a fast piezo tuner, the stability improves to 2.8° (blue curve).

existing TTF couplers can readily handle, as demonstrated in HoBiCaT [10]. The STARS system will consist of 20 individual IOT-based RF transmitters supplying one cavity each via coaxial transmission lines. RF control will be performed by a digital FPGA-based system.

BEAM TRANSPORT

A single bunch compressor at 180 MeV is required to increase the peak current. A combination of off-crest acceleration and subsequent passage through a dispersive magnetic chicane is employed to compress the beam from 45 A to 500 A.

Due to non-linearities in the accelerating RF potential, a very high and short current peak with a long tail results after the compression. As the peak will generate strong SASE background radiation, it limits the compression factor and hence the power of the HGHG output radiation. Although STARS is designed to be able to demonstrate HGHG in this mode, the quality and power is improved upon by installing third-harmonic cavities. They remove most of the non-linearities of the RF potential and the bunch compressor. A superconducting third-harmonic module (with four 9-cell cavities) is currently being developed by Fermilab for the FLASH accelerator [13]. This unit is compatible with the main acceleration modules and is planned for installation in March 2008. Preliminary analyses of the input coupler system suggest that CW operation of the unit is also possible.

Start-to-end tracking of the electron beam, including all components in Figure 1, have been completed. The photoinjector and the first four cavities were simulated with ASTRA to take into account space-charge effects. ELEGANT was used for the remainder of the linac, while tracking in the undulators was performed with GENESIS.

The bunch profile at the entrance of the undulators is depicted in Figure 4. A *slice* emittance of approximately 1 π mm mrad and an energy spread of 12 keV is predicted. Very important for the HGHG process is the fact that a constant profile is maintained in the approximately 1-ps wide peak-current region (500 A) used in the HGHG cascade.

Measurements at PITZ have demonstrated that a *projected* emittance of approximately 1.5 π mm mrad is readily achievable [6, 7]. Also, tests at FLASH have shown that there the energy spread is below the measurement resolution limit of 20 keV [14]. Both results are compatible with the predicted beam parameters for STARS. Nevertheless, for subsequent GENESIS simulations, the *slice* beam emittance was intentionally increased to 1.5 π mm mrad to provide for an additional safety margin in case unexpected beam dilution occurs in the STARS linac. An improved emittance will allow STARS to operate at higher power.

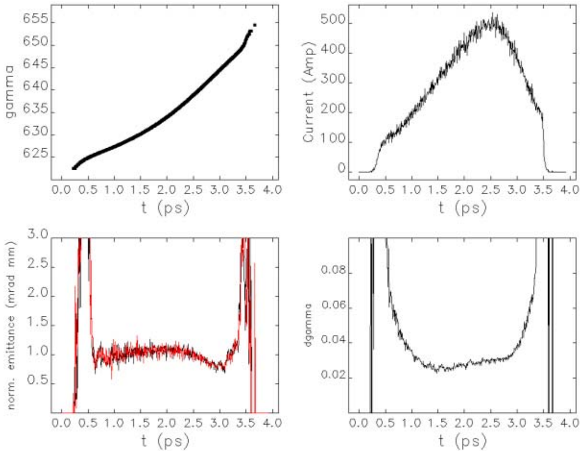

Figure 4: Simulated beam properties at the entrace of the undulator. Top left: Beam energy, top right: current profile, bottom left: slice emittance, bottom right: slice energy spread.

An important consideration for the HGHG cascade is the bunch-to-bunch stability of the beam. Due to the off-crest acceleration, the bunches have an energy chirp of about 5 MeV/ps. Any time jitter of the bunches thus shifts the central energy of the slices used for HGHG which must remain in the energy acceptance of the cascade (of order 2×10^{-3}). Hence the jitter of the seed laser to the bunch may not exceed about 150 fs. Studies of the jitter are still ongoing, but first results based on the cavity performance in HoBiCaT have demonstrated that the required stability can be achieved with the CW SRF system.

THE HGHG CASCADE

STARS will cascade two HGHG stages to reach a photon energy of up to 31 eV. Even higher energies can be accessed by tapping into the harmonic content of the radiation.

Figure 5 depicts the layout of the STARS HGHG cascade. STARS will be continuously tunable from 40 nm to 70 nm, the lowest wavelengths placing the most stringent requirements on the electron beam quality. The flexibility is achieved by using different harmonics (three to five) in the cascades in conjunction with gap adjustments of the undulators and variation of the seed wavelength.

Modulators 1 and 2 and Radiator 1 are planar devices, while APPLE-III undulators for Radiator 2 provide full variability of the polarization between 40 nm and 50 nm [15]. APPLE-III devices yield a 35% higher field on axis than APPLE-II undulators, so that at minimum gap

Figure 5: Schematic of the STARS HGHG cascade (note that the quadrupoles between undulators are not shown.)

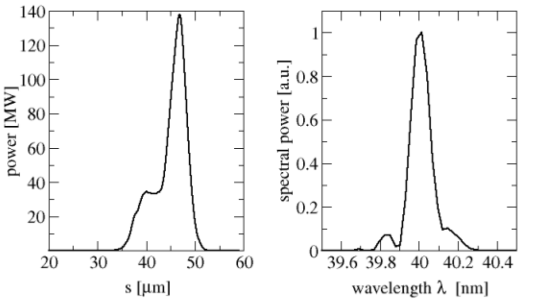

Figure 6: Temporal profile (left) and spectrum (right) of helical radiation at 40 nm.

(7 mm) 70 nm radiation is within reach. Here, the required electron-beam quality is relaxed and STARS can even be commissioned without the third-harmonic cavity system.

Performance predictions for the HGHG process were made using complete start-to-end simulations with the same approach as for the BESSY FEL [16, 17, 18]. Importantly, the HGHG simulations with GENESIS 1.3 are based on the actual electron bunch profiles obtained from the linac start-to-end calculations, only that the slice emittance has intentionally been increased by 50%. Also, both radiating slices have been tracked through the first HGHG stage to ensure that any (detrimental) spontaneous radiation is taken in consideration.

Results for the most challenging case, radiation produced at 40 nm, are depicted in Figure 6 [18]. For helical polarization, an output power of order 140 MW is expected. The length of the seed-laser pulse (approximately 20 fs) is maintained and about 53% of the power is within the 0.1% spectral bandwidth. Even more power is produced at longer wavelengths—nearly 350 MW at 66 nm.

Significant flexibility has been designed into STARS for the final radiator. Here three independent modules are used to permit a wide range of operating modes. One benefit is that STARS is very tolerant to variations of the electron-beam parameters, with saturation attained either after the first or second module. Figure 7 underscores this point for simulations at 40 nm (planar polarization). Two simulations were performed; one with the beam emittance and energy spread as predicted by the start-to-end simulations (1 π mm mrad and 3×10^{-5}, respectively) and one with the emittance and energy spread increased to 1.5 π mm mrad and 10^{-4}, respectively. In the latter case, the strength of the dispersive section had to be increased and the second module of Radiator 2 was closed. Nevertheless, nearly the same output performance is achieved.

At the expense of spectral purity and by employing all three radiator modules, the power can be increased further by driving the cascade in the superradiance regime. This mode is able to achieve peak powers above 1 GW at 40 nm (see [18] for more details). Wavelengths below 40 nm are also within reach of STARS by tapping into nonlinear harmonic contents of the radiation field. For example, using the third-harmonic (13 nm) approximately 700 kW is expected [18, 19].

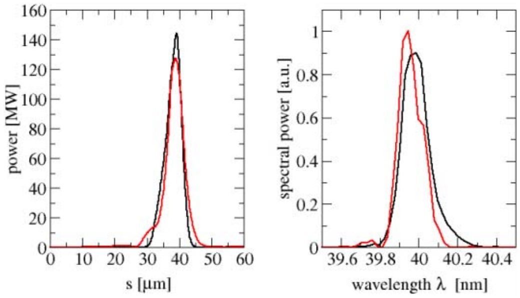

Figure 7: Simulated performance at 40 nm (planar polarization). The black curves were obtained with an emittance of 1 π mm mrad and an energy spread of 3×10^{-5}. The calculations were repeated with degraded values of 1.5 π mm mrad and 10^{-4}, respectively (red curve) and the 2nd module of Radiator 2 was closed.

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