STARS – A TWO–STAGE HIGH–GAIN HARMONIC GENERATION FEL DEMONSTRATOR

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Abstract

BESSY is proposing a demonstration facility, called STARS, for a two-stage high-gain harmonic generation free electron laser (HGHG FEL). STARS is planned for lasing in the wavelength range 40 to 70 nm, requiring a beam energy of 325 MeV and peak current of 500 A. The facility consists of a normal conducting gun, three superconducting TESLA-type acceleration modules modified for CW operation, a single stage bunch compressor and finally a two-stage HGHG cascaded FEL. This paper describes the faciliy layout and the rationale behind the operation parameters.

MOTIVATION

Ultra-short pulses from single-pass free-electron lasers are unique tools for future time resolved experiments. In March 2004, BESSY published a TDR for a Soft X-Ray Free Electron Laser user facility (BESSY FEL) [1] in the photon range from 24 eV to 1 keV, based on the High-Gain Harmonic Generation (HGHG) principle [2]. 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. Following the evaluation of the TDR, the German Science Council recommended funding the BESSY FEL subject to the condition that its key technology, the HGHG cascade, be demonstrated beforehand. BESSY is therefore proposing a two-stage HGHG cascade to address this important issue. This facility is called STARS and many of the components and technical issues are identical or very similar to those of the BESSY FEL. Hence, even though the emphasis of STARS will be to demonstrate the HGHG cascade, it will also serve as an ideal test bed for operating TESLA technology in CW, diagnostics, synchronization, and first user experiments.

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OVERVIEW

The STARS layout is shown in Fig. 1. 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 MeV. The cryomodules contain twenty 9-cell TESLA type cavities. A bunch-compressor section is placed between the second and third module. The last acceleration module is followed by a diagnostics beamline and a collimator to protect the downstream HGHG cascade.

ELECTRON BEAM GENERATION

The electron beam for STARS is generated in a normal conducting photoinjector. A UV photocathode-laser illuminates a cesium-telluride cathode with flat-top laser pulses of 20 ps width to release electron bunches of 1 nC charge and 30 A peak current. The STARS injector will initially be operating at a repetition rate of 100 Hz, with the option to increase this to 1 kHz at a later stage. Given an RF pulse length of 25 μs, the duty factor is 0.25%. Thermal loading (7.5 kW) will therefore not be an issue, in fact the reduced load with short pulses improves the stability of the RF system. If 1 kHz operation is realized at a later date, 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 [4].

ACCELERATION

Superconducting RF technology developed by the TESLA collaboration and as described in the BESSY FEL TDR [1] has been chosen for the CW linear accelerator for STARS. To confirm the suitability for CW operation, BESSY has already worked on an intensive qualification program. Tests of RF couplers [5] and tuners [6] as well as studies, such as the optimum bath temperature required for reliable and economic CW operation, have been performed. The Horizontal Bi-Cavity Test facility [7] has been set up for this purpose.

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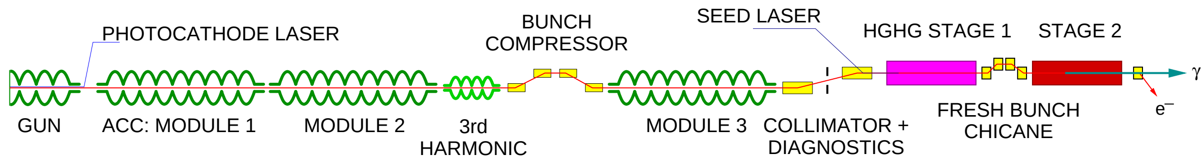

Figure 1: Layout of the main components of STARS.

Simulations of the HGHG scheme have shown that a beam energy of 325 MeV is sufficient for lasing at a wavelength down to 40 nm. This energy can be reached with three TESLA-type modules containing a total of 20 cavities. Ideally all cavities will operate at the same nominal voltage. Hence, given an injection energy of 4 MeV out of the photoinjector and an acceleration phase of 14 deg before the bunch compressor, the cavities need to operate at 17.2 MeV/m. Note that this value takes into account a total decelerating voltage of about 30 MeV in the third harmonic section.

At 1 nC bunch charge and a repetition rate of 100 Hz, beam loading in STARS is less than 2 W per cavity and therefore negligible. Hence, RF power will be needed primarily to compensate the microphonic detuning in the cavities. 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. Means to reduce these are being investigated [8], but it is anticipated that the large volume of the STARS helium system will reduce the RMS fluctuations further. Hence, for STARS 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 $2.6 \cdot 10^7$. At 17.2 MV/m accelerating field this translates into an RF power requirement of $\bar{P} = 3.1$ kW and $P_{peak} = 5.9$ kW, which can be readily handled by the existing TTF couplers. The STARS system will consist of 20 individual RF transmitters supplying one cavity each with up to 10 kW RF power via coaxial transmission lines. RF control will be performed by a digital FPGA-based system.

BUNCH COMPRESSION

A magnetic chicane is needed to compress the beam charge intensity distribution to high current. Here bunch compression is performed with a two step procedure, off-crest acceleration and subsquent passage through a magnetic chicane. Non-linearities in the accelerating RF potential result in a very high and short current peak unsuitable for seeding in the HGHG cascade because it will generate strong SASE background radiation. In order to counteract this, a 3rd harmonic section is included in the machine layout.

A single bunch compressor at about 180 MeV energy will be sufficient because only a moderate compression factor of order 11 is required to achieve the full 500 A peak current. Simulation results of the bunch distribution are shown in Fig. 2. The sliced emittance is conserved in both planes as well as the energy spread (apart from the increase related to the energy chirp used for the compression scheme).

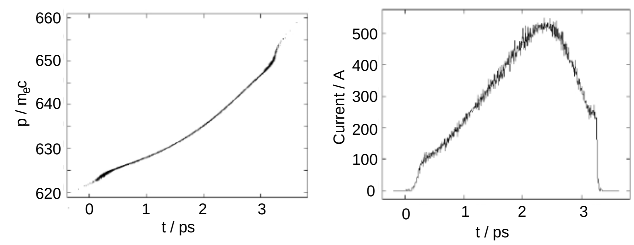

Figure 2: Simulated longitudinal phase space (left) and corresponding current distribution (right) of the electron bunches at the undulator entrance.

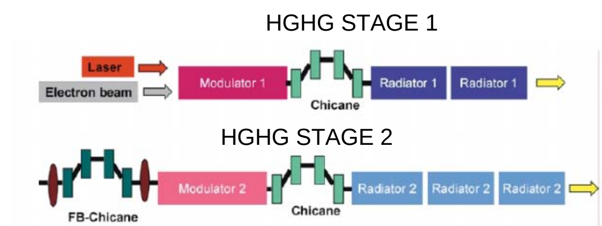

Figure 3: Schematic of the STARS two-stage HGHG cascade.

HGHG CASCADE

STARS will cascade two HGHG stages to reach a photon energy of up to 31 eV, with even higher energies accessible by tapping into the harmonic content of the radiation. In Fig. 3 the general layout of the STARS HGHG cascade is shown. STARS will be continuously tunable from 40 nm to 70 nm. This high degree of 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. Full variability of the polarization is possible between 40 nm and 50 nm by using APPLE-III undulators [11] for the second radiator. Performance predictions for the HGHG process were obtained from complete start-to-end simulations with the same approach as for the BESSY FEL [9, 10]. In particular, the HGHG simulations are based on the actual electron

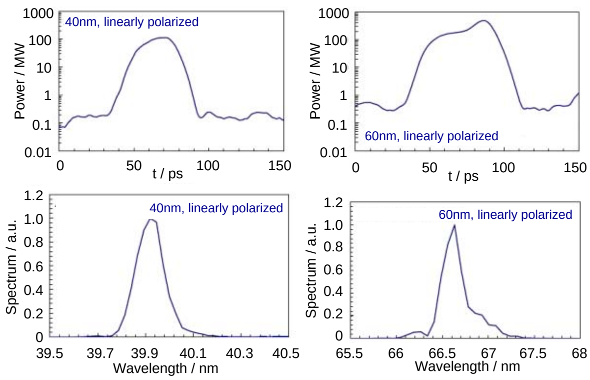

Figure 4: Temporal FEL pulse and spectra for STARS output radiation at 40 nm and 66 nm.

bunch profiles obtained from the linac start-to-end calculations. Examples for linearly polarized output radiation after the first module of the final amplifier are shown in Fig. 4. Peak powers of over 100 MW (at 40 nm) and over 400 MW (at 66 nm) can be achieved. The pulse length is of order 20 fs FWHM, reproducing the short pulse duration of the seed laser used. The spectral bandwidth is 0.36% in both cases. Even higher power levels are possible for helically polarized light. Here peak powers of 200 MW at 40 nm and well over 600 MW at 50 nm are achieved. At the expense of spectral purity, the power can be increased further by driving the cascade in the superradiance regime, when the second and third modules of the final amplifier are used. Wavelengths below 40 nm are also within reach of STARS by tapping into nonlinear harmonic contents of the radiation field. Wavelengths down to 13 nm are accessible if the 3rd harmonic is used [12].

EVALUATING EXPERIMENTS

The experiments planned for STARS are designed to demonstrate the scientific capabilities of the HGHG FEL source. Specifically, the experiments address applications that require the coherence and the controlled, reproducible pulse shape of such a source. Hence, for the direct FEL beam the demonstration experiment covers the general area of time resolved (coherent) imaging, whereas the monochromatized beam will be used to demonstrate STARS' time resolved spectroscopy capabilities. As depicted in Fig. 5, two femtosecond x-ray pulses hit a sample in close succesion, with a well controlled time delay between the two pulses, ranging from a few femtoseconds up to 25 picoseconds. Future research opportunities in solid-state physics exist in the areas of magnetic and lattice excitations, dynamics of glasses and liquids, excitations in Bose-Einstein condensates and critical fluctuations.

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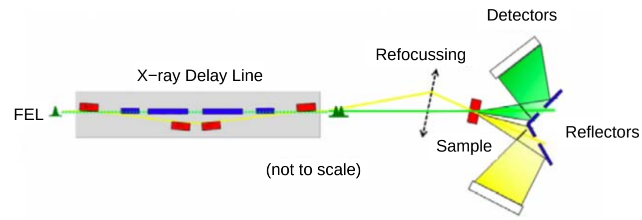

Figure 5: Optical layout of the time-resolved imaging experiment in the angular separation mode.

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