SMALL-APERTURE VACUUM-CHAMBER DESIGN FOR STARS*

J. Bahrdt, V. Dürr, A. Meseck†, M. Scheer, G. Wüstefeld
BESSY GmbH, Berlin, Germany

Abstract

To demonstrate and investigate the cascaded high-gain harmonic generation (HGHG) scheme proposed for the BESSY Soft X-ray FEL, BESSY plans to build a test-facility called STARS consisting of two HGHG stages. The radiator in the second stage is planned as an APPLE III device which provides the highest field for a circular beam pipe. It's minimum Gap of 7 mm translates into a 5 mm inner diameter of the vacuum chamber, which leads to a higher pressure and an increase of the wakefields. An analysis of the impact of the wakefields and the expected vacuum profile is thus required. Results of this analysis and vacuum calculations and measurements are presented.

INTRODUCTION

To provide radiation with high power, short pulse length and full coherence in the VUV and soft X-ray regime, BESSY plans to build a seeded FEL facility based on the high-gain harmonic generation scheme [1, 2]. The technical design report of the BESSY Soft X-ray FEL facility [3] was evaluated in 2006 by the German Science Council and recommended for funding subject to the condition that its key technology, the cascaded HGHG scheme, be demonstrated beforehand. To address this issue, BESSY is proposing the proof-of-principle facility STARS [5] for a two-stage HGHG cascade which will serve as a user facility even after the commissioning of the BESSY FEL. The STARS is seeded by a tunable laser covering the spectral range of 700 nm to 900 nm. The target wavelength ranges from 70 nm to 40 nm with peak powers up to a few hundred MWs and pulse lengths less than 20 fs (rms). The polarization of the fully coherent radiation is variable. For efficient lasing a 325 MeV driver linac is required. It consists of a normal-conducting gun, superconducting TESLA-type modules modified for CW operation and a bunch compressor, for more details see please [4, 5, 6].

The STARS comprises a cascade of two HGHG stages each consisting of an undulator (acting as modulator) / dispersive chicane / undulator (acting as radiator) section. The two modulators and the first radiator of the STARS are planned as planar devices. The second (final) radiator needs to be helical to provide full polarization control of the output radiation. This radiator consists of three undulator modules and will be realized as an APPLE III [7] device.

The period lengths and the minimum gaps, i.e. free aperture between the magnet rows, of the undulators are chosen such that the desired wavelength range can be covered for an electron beam energy of 325 MeV. The planar devices have a period length of 50 mm and a minimum gap of 20 mm and 10 mm respectively. The period length of the final radiator amounts to 22 mm and the minimum gap is 7 mm. This small gap translates into 2.5 mm for the vacuum chamber inner radius.

Generally, the small conductance caused by such a small aperture leads to a higher pressure, which has to be counteracted by a suitable vacuum pumping scheme as far as possible. An other impact of the small aperture is the enhancement of the wakefields. In spite of the moderate peak current of 500 A predicted for STARS, an increase of the undulator wakefields can be expected.

The degradation of the electron beam quality due to the higher pressure and the change in the electron energy by the wakefields decline the FEL output radiaton. We present a analysis of their impact on the FEL performance.

CIRCULAR BEAM PIPE AND APPLE III TYPE RADIATOR

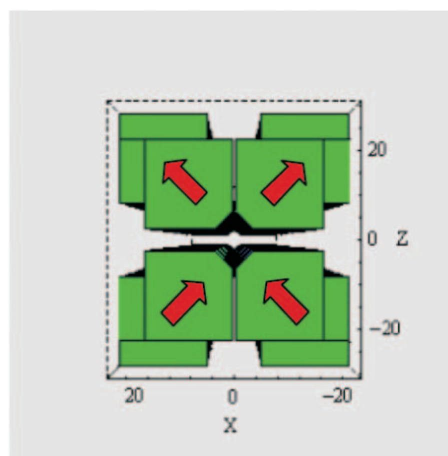

Figure 1: A sketch of the magnetic structure of an APPLE III device.

The second radiator will be realized as an APPLE III device providing full polarization control of the radiation. This APPLE type requires a round beam pipe to allow for more magnetic material located close to the electron beam, see Figure 1. For the second radiator of STARS, the free aperture between the magnets is 7 mm and the smallest vertical distance amounts to 4.4 mm which provides enough space for Hall probe measurements as well as for a fixture to support the vacuum chamber. An APPLE III type structure has been chosen for a number of reasons:

* Work supported by the Bundesministerium für Bildung und Forschung and the Land Berlin
† meseck@bessy.de

- For the same minimum aperture (7mm in this case) the APPLE III device provides a factor of 1.35 higher fields when compared to the APPLE II design. Note that the minimum aperture of 7 mm is limited by the acceptable aperture of the electron collimation system and the alignment concept.
- The natural focusing of an APPLE III design is smaller than that of an APPLE II. The natural focusing depends on the transverse field profiles which changes with gap and row phase of the variably polarizing Radiator. The focusing strength has an impact on the electron beam size and has to be compensated by a superposed external quadrupole lattice.
- The APPLE III design provides space for the installation of glass fiber radiation monitors (to detect beam loss) close to the electron beam without sacrificing gap (the diameter of Cherenkov glass fibers is 0.7mm) [8, 9].

However, the needed circular beam pipe with the small inner radius of 2.5 mm reduces the vacuum conductance, even more than an elliptical beam pipe with a short axis of 2.5 mm. Therefore a suitable pumping scheme has been designed.

VACUUM SYSTEM

A carefully designed pumping system for the second radiator requires 3 m long modules with 1 m long sections between them. The intersections will comprise the pump,focussing quadrupoles, phase shifter and diagnostic. Figure 2 shows the calculated vacuum profile for this scheme. The peak value is in the 10^{-6} mbar range. Measurements with a commercially available copper tubing (with a inner radius of 2 mm) have yielded a value of 5×10^{-7} mbar. After several weeks of measurement the pressure fell to 2×10^{-8} mbar. Therefor pressures less than 1×10^{-7} mbar can be expected for the final radiator.

Gas pressures in this range are not expected to produce significant radiation damage in the undulators or impact the photon flux. The question, whether the elastic scattering on nuclei, which provides the major contribution to the scattering process for 300 MeV electrons, can cause a noticeable angle error, has been investigated by analytical models [10, 11, 12] and Monte-Carlo simulations. The results of the calculation and simulations with GEANT3 and GEANT4 [13, 14] are summarized in Figure 3. Depicted is the number of scattered electrons per solid angle versus the scattering angle (for 300 MeV electrons). The electrons are scattered on N_2 in a target length of 4 m with a pressure of 10^{-5} mbar. Most electrons are scattered in a very small angle, less than 0.01% have a scattering angle larger than 10 μrad. Therefore, for a vacuum pressure less than 10^{-5} mbar the scattering on rest gas can be neglected.

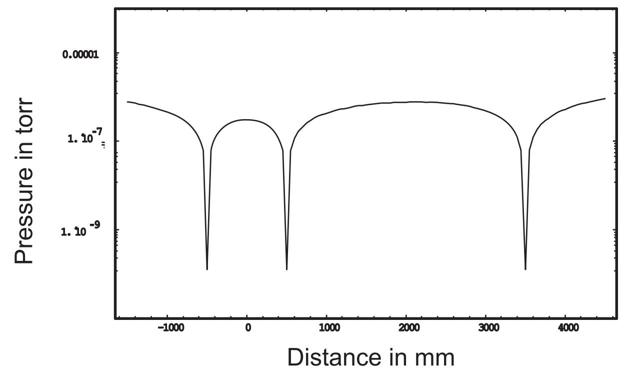

Figure 2: The calculated vacuum profile of the second radiator with a module length of 3 m.

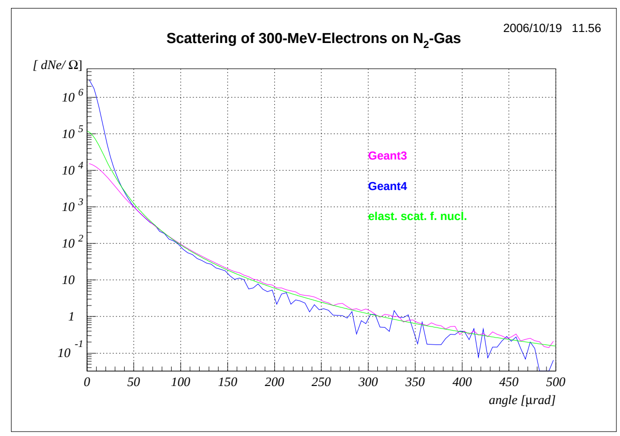

Figure 3: The number of scattered electrons per solid angle versus the scattering angle for 300 MeV electrons scattered on N_2 in a target length of 4 m with a pressure of 10^{-5} mbar.

WAKEFIELDS

Due to the small aperture of the second radiator, measurable wakefields are expected in spite of the low peak current of 500 A. The change of the electron energy by these wakefields could perturb the FEL interaction by pushing the electrons off-resonance. An analysis of the wakefields was performed to estimate their impact on the FEL performance.

Figure 4 shows the temporal profile of the wakefields, where the black line is the resistive wake, the blue line is the geometrical wake, the red line is the sum of them and the green line is the current profile. Two examples are shown for different inner radii (r) of a copper pipe. The aperture for the diagnostic box (gap) is 20 mm. The temporal profile of the wakefields for different aperture of diagnostic box are depicted in Figure 5, also an example with aluminum pipe is shown.

The dominant sources were found to be the resistive wall wakes and the effect of geometry at the diagnostic ports, each contributing about 50% to the total wakefield. Maximum calculated values were of order 5 kV/m for a pipe inner radius of 2.5 mm.

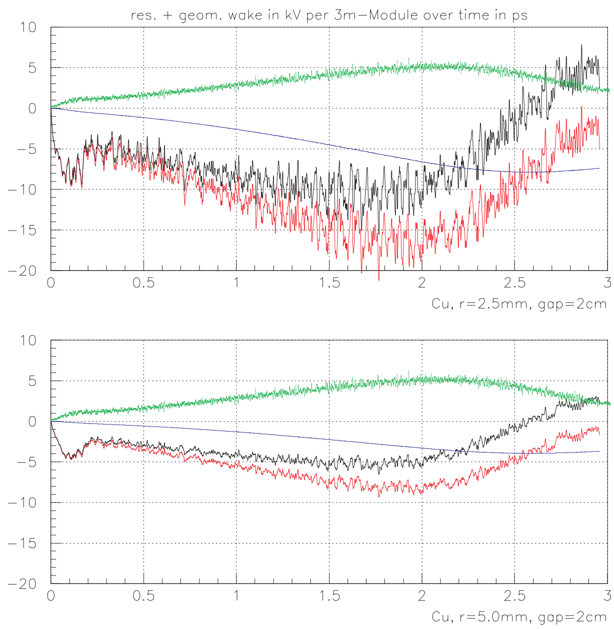

Figure 4: Temporal profile of the wakefields, where the black line is the resistive wake, the blue line is the geometrical wake, the red line is the sum of them and the green line is the current profile in [a.u.].Two examples are shown for different inner radii (r).

Compared with published LCLS wakefield calculations [15, 16] the peak current in STARS is more than 20 times smaller and in turn much weaker wakefields are expected. There is no advantage of the use of aluminum pipe for the second radiator of STARS, see Figure 5. Note that for STARS the AC component of the resistive wall wakefields can be neglected, as the STARS bunch ($500\mu m$ rms [6]) is much longer than the LCLS bunch ($20\mu m$ rms [15]).

The energy loss due to the wakefields (5 keV/m) was included in the calculation of the FEL radiation using GENESIS [17]. Figure 6 compares the FEL performance with and without the energy loss. The temporal and spectral profiles of the FEL output are shown for the shortest target wavelength of STARS. For a beam pipe with a inner radius of 2.5 mm and the expected beam properties of STARS, the impact of the wakefields is negligible.

CONCLUSION

A small-aperture vacuum-chamber with an inner radius of 2.5 mm is planned for the second radiator of STARS. Generally, such a small aperture leads to a higher pressure and an increase of the wakefields. Thus it causes a degradation of the FEL output.

The expected pressure and its impact on the electron beam has been calculated for the second radiator. Additionally, the pressure was measured in a test setup. The

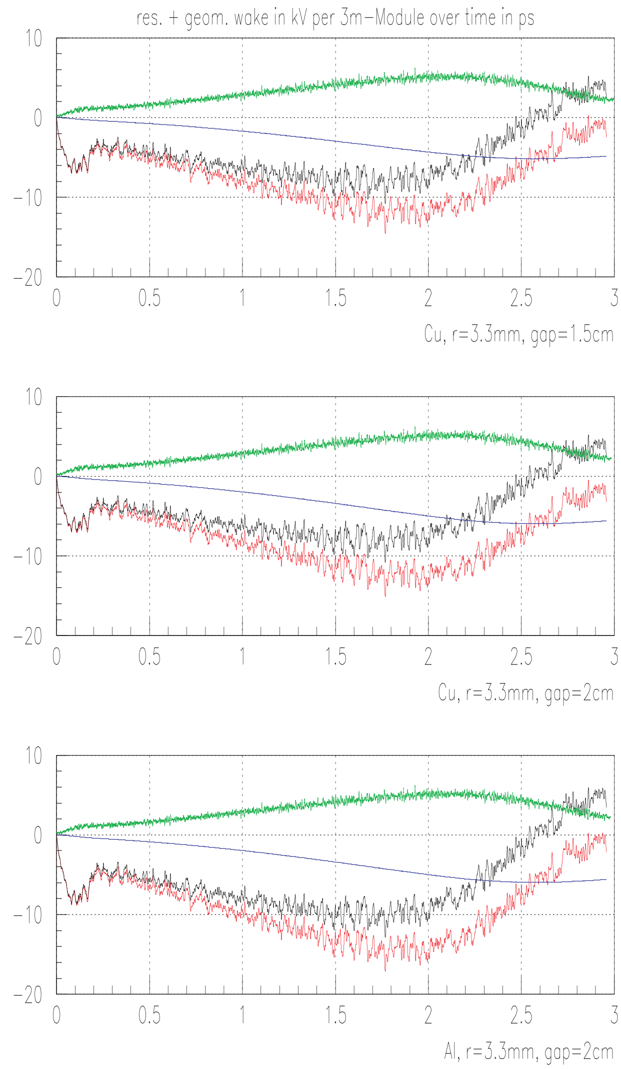

Figure 5: Temporal profile of the wakefields, where the black line is the resistive wake, the blue line is the geometrical wake, the red line is the sum of them and the green line is the current profilein [a.u.]. Three examples are shown for different aperture of diagnostic box (gap) and materials.

increase of the pressure seems to be very moderate. Thus the electron beam will not be disturbed.

Due to the wakefields, an energy loss of 5 keV/m is expected for the second radiator. Including this in the FEL simulations, almost no impact could be observed. We conclude that the small-aperture beam-pipe of the second radiator causes almost no degradation of the FEL performance.

REFERENCES

[1] L. Yu,“Theory of high gain harmonic generation: an analytical estimate ,” NIM A 483 (2002) 493.

[2] L. Yu, “High-gain harmonic generation of soft X-ray with the “fresh bunch” technique,” NIM A 393 (1997) 96.

[3] “The BESSY Soft X-ray Free Electron Laser, Technical De-

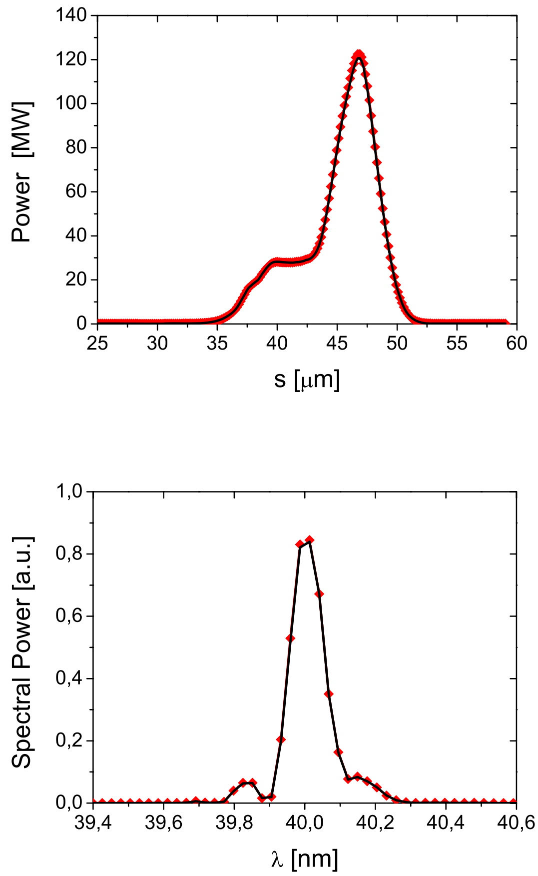

Figure 6: Temporal (top) and spectral (bottom) profiles of the FEL output are shown for the shortest wavelength (i.e. 40 nm) aimed at STARS with (black line) and without (red diamond) the energy loss due to the wakefield.

sign Report", March 2004, eds.: D. Krämer, E. Jaeschke, W. Eberhardt, ISBN 3-9809534-08, BESSY, Berlin (2004).

[4] B. Kuske, K. Goldammer, A. Meseck, "Output Performance of the STARS HGHG Demonstrator at BESSY", this conference.

[5] "STARS - Proposal for the Construction of a Cascaded HGHG FEL", eds.: J. Knobloch, E. Jaeschke, W. Eberhardt, BESSY, Berlin (2006).

[6] T. Kamps et al., "STARS - A Two-Stage High-Gain Harmonic Generation FEL Demonstrator", proceedings PAC07.

[7] J. Bahrdt, W. Frentrup, A. Gaupp, B. Kuske, A. Meseck, M. Scheer, "UNDULATORS FOR THE BESSY SOFT-X-RAY FEL", proceedings FEL 2004, Trieste, Italy.

[8] J. Bahrdt,"APPLE UNDULATORS FOR HGHG-FELS",proceedings FEL 2006, Berlin, Germany.

[9] J. Bahrdt," Status of the Undulator System of the Seeded HGHG-FEL Test bench at MAX-Lab", this Conference

[10] J.D. Jackson, "Classical Electrodynamics", 2.Edition (1975).

[11] W. A. McKinley, "The Coulomb Scattering of Relativistic Electrons by Nuclei", Phys.REV.74 (1948) 1759.

[12] J. Le Duff, "Current and Current Density Limitations in Existing Electron Storage Rings," NIM A 239 (1985) 83.

[13] S. Agostinellia et al.,"GEANT4 - A Simulation Toolkit", NIM A506 (2003), 250-303R. Brun et al.

[14] "GEANT Detector Description and Simulation Tool", v. 3.21, CERN Program Library CERN (1993).

[15] K. L. F. Bane, G. Stupakov, "Resistive Wall Wakefield in the LCLS Undulator", proceedings PAC05.

[16] S. Reiche et al., "Optimization of the LCLS X-ray FEL output performance in the presence of strong undulator wakefields", proceedings PAC05.

[17] S. Reiche, "GENESIS 1.3", NIM A 429(1999) 243.