THE IMPACT OF SPACE CHARGE ON THE STARS PERFORMANCE*

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Abstract

BESSY is proposing a two-stage high-gain harmonic generation (HGHG) FEL , STARS [1], to demonstrate and investigate the cascading proposed for the BESSY Soft X-ray FEL [2]. STARS will have a target wavelength range from 70 nm to 40 nm with peak powers up to a few hundred MWs and pulse lengths less than 20 fs (rms). In an HGHG stage an energy modulation is imprinted to the electron beam by a seeding radiation. A dispersive section converts this energy modulation to a spatial modulation which is optimized for a particular harmonic. The subsequent radiator is optimized for this harmonics and generates radiation with high power which is used as seeding radiation for the next stage. During the passage through the dispersive section, subsequent drifts and the radiator, space charge effects can reduce the generated bunching and degrade the FEL performance. We present simulation studies for the impact of the space charge forces in the undulator section on STARS performance.

INTRODUCTION

High power, short pulse length and full coherence are the main parameters of the second generation free electron lasers. To provide radiation with these properties in the VUV and soft X-ray regime, BESSY plans to build a seeded FEL facility based on high-gain harmonic generation scheme [2]. This scheme uses cascaded stages each consisting of undulator/dispersive chicane/undulator section to up-convert the seeding frequency.

To demonstrate the cascaded HGHG scheme beforehand, as recommended by the German Science Council, BESSY is proposing the proof-of-principle facility STARS for a two-stage HGHG cascade [1]. 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 will be variable. For efficient lasing a 325MeV driver linac is required. It consists of a normal-conducting gun, superconducting TESLA-type modules modified for CW operation, and a bunch compressor.

In the first undulator of an HGHG stage, the so called modulator, the interaction with a radiation field (e.g. provided by an external laser) leads to an energy modulation of the electron beam with the period of the seeding wavelength. The following dispersive section converts this energy modulation into a density modulation, or bunching, that includes higher harmonics of the seeding frequency. The fundamental of the second undulator, the so called radiator, is set in resonance with the chosen harmonic. The prebunched beam then radiates at the harmonic wavelength with high efficiency. The radiator output is used as the seed for the next stage allowing cascading the HGHG-stages.

For the performance calculation of such an HGHG cascade as well as during the design work, the effect of the longitudinal and transverse space charge forces in the density modulated beam has to be taken into account, as they can reduce the generated density modulation and blow up the transverse beam dimensions, respectively. Using suitable quadrupol magnets the impact of the transverse space charge forces on the dimensions of the beam can be reduced significantly. However, the reduction of the density modulation caused by the longitudinal space charge force can not be counteracted so easily. It diminishes the bunching during the passage through the dispersive chicane, subsequent drifts and the radiator, thus it reduces the radiator output. Therefore the space charge forces in the density modulated beam can degrade the FEL output.

In order to investigate the output degradation due to the longitudinal space charge, simulation studies in the undulator section of STARS have been performed, using the 3D time-dependent FEL code GENESIS [6] which includes longitudinal space charge forces. In this paper, the simulation studies for the impact of the space charge forces in STARS are presented.

THEORY

In the cascaded HGHG scheme, the necessary seeding power for each stage is produced by adjusting the output power of the previous stage. The output power of the radiator is proportional to the square of the bunching factor, b_n. The bunching factor for the n^{th} harmonic of the seed laser is given by:

$$
\begin{aligned}
b_n &= \langle \exp(i\, n\, \theta_j) \rangle \\
&= \exp\left(\frac{-1}{2} \sigma_\gamma^2 \left(\frac{d\psi}{d\gamma} \right)^2 \right) J_n \left(\Delta\gamma \frac{d\psi}{d\gamma} \right),
\end{aligned}
$$

where θ is the ponderomotive phase of the electron beam in the modulator, $\psi = n\theta$ is the phase in the radiator, $\Delta\gamma$ is the maximum energy modulation generated in the modulator, σ_γ is the energy spread of the electron beam, $\frac{d\psi}{d\gamma}$ is the strength of the dispersive section and J_n is the n^{th} order

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Bessel function. Proper bunching factors can be achieved when the energy modulation impressed by the seed dominates the energy spread of the electron beam. For a reasonable performance of an HGHG stage the energy modulation induced by the seed should fulfill the following inequality [3]:

$$\Delta\gamma \geq n\sigma_\gamma.$$

The dispersive section has to be adjusted according to the energy modulation, reached in the modulator, taking the effective dispersion in the modulator and radiator into account.

In general, the radiators in an HGHG cascade are short. Avoiding the exponential gain regime, the high output power of the radiator is due to the prebunching of the beam. Thus the bunching development in the dispersive section, subsequent drifts and the radiator itself are of major interest for the radiator output. As mentioned before the longitudinal space charge force can degrade the bunching.

As the evolution of a bunch of relativistic charged particle under the influence of the its own field is very complex, only a few three dimensional self-consistent analytical treatments of the space-charge waves within a relativistic beam exist, e.g. [7]. However a good insight of the impact of the longitudinal space charge forces on the bunched beam can be obtained from the 1D treatment of the problem as developed in [8, 9]. For a sinusoidal prebunched beam with a bunching parameter, $b(k)$, the on-axis longitudinal electric field in free space is [8]:

$$E_z(k) = -\frac{4ien_0 b(k)}{kr_b^2}\left(1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right),$$

where n_0 is the average line density, k is the modulation wavelength, r_b is the beam radius for a circular cross section, K_1 is the modified Bessel function, and the velocity of the electrons is taken to be the speed of light c. Note that the small transverse variation of E_z are neglected. The longitudinal field tends to push electrons away from each other, accelerating the front electrons and decelerating the back electrons. Thus it transfers the density modulation into an energy modulation. Due to the momentum compaction, R_{56}, in the drifts and magnetic sections, this energy modulation converts back to density modulation thus completing space charge oscillations.

The longitudinal free space space charge impedance per unit length is [9].:

$$Z_{LSC}(k) = \frac{4i}{kr_b^2}\left(1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right). \quad (1)$$

For beam pipe radius much larger than the reduced modulation wavelength, $\gamma\lambda/2\pi$, the free space approximation is satisfied. The frequency of the space charge oscillation, Ω, is given by [9]:

$$\Omega = c\left(\frac{I_0}{I_A\gamma^3}k|Z_{LSC}|\right)^{1/2}, \quad (2)$$

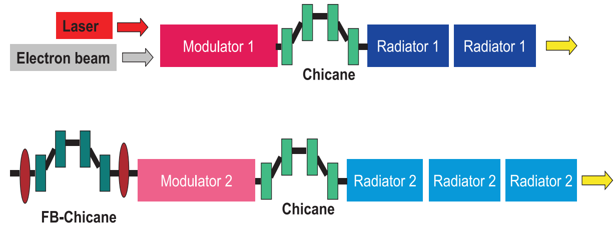

Figure 1: A schematic view of the STARS FEL line.

where I_0 is the peak electron current, and $I_A = 17.045$ kA is the Alfen current. The corresponding density and energy modulation in a drift section are [9]:

$$b(k) = b_0(k)\cos\Omega/c \quad (3)$$

$$\Delta\gamma_{sc} = -\frac{I_0}{I_A}Z_{LSC}b_0(k)\frac{\sin\Omega/c}{\Omega/c}. \quad (4)$$

From the above formulas it can be concluded that for the high current low energy electron beams, where the oscillation frequency is high, the impact of the longitudinal space charge force on the FEL output is not negligible. Therefore this effect is taken into account for performance calculation of STARS.

STARS

The demonstration facility STARS will consist of two HGHG-stages fed by a 325 MeV driver linac. It is seeded by a tunable laser. The desired wavelengths cover the spectral range of 70 nm to 40 nm with peak powers up to a few hundred MWs and pulse lengths less than 20 fs (rms). Figure 1 shows a schematic view of the FEL line.

The high degree of wavelength tunability is achieved by using different harmonics in the cascade in combination with the gap adjustments and seed wavelength variations. The radiators consist of several undulator modules allowing for an additional adjustment of the radiator length, by a proper opening of the gaps to the maximum value. The opened module is like a drift as no magnetic field acts on electrons. In this way the radiator length can be varied. In order to avoid a degradation of the seed properties for the next stage, the position of the radiation source point has to remain fixed. Therefore only the first few modules after the dispersive chicane can be opened in such a way.

However in a drift space after the dispersive section, the longitudinal space charge force can cause an oscillation in bunching factor according to equ. 3. Fig. 2 shows an example for the bunching oscillation for the open radiator modules in case of the STARS. For the presented calculations, we assume an electron beam with a peak current of 500 A, transverse normalized slice emittances of 1 mm mrad and an rms energy spread of 10 keV. The seed wavelength is 800 nm and the resonant wavelength of the radiator amounts to 160 nm. The undulator modules of the

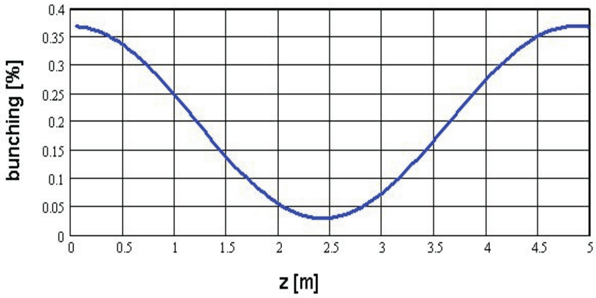

Figure 2: Bunching oscillation in a drift space after the dispersive section due to the longitudinal space charge force according to equ. 3.

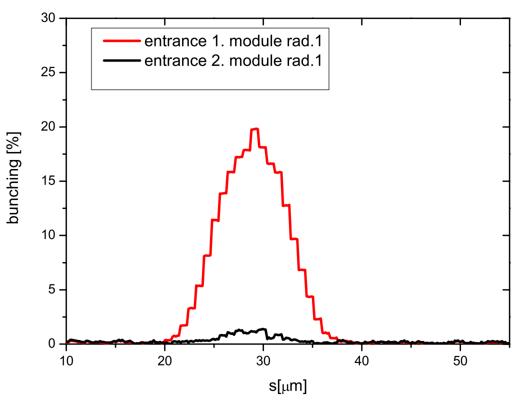

Figure 3: Bunching at the entrance of the first and second radiator module.The bunching develops due to the momentum compaction of the drift which is inversely proportional to the beam energy square.

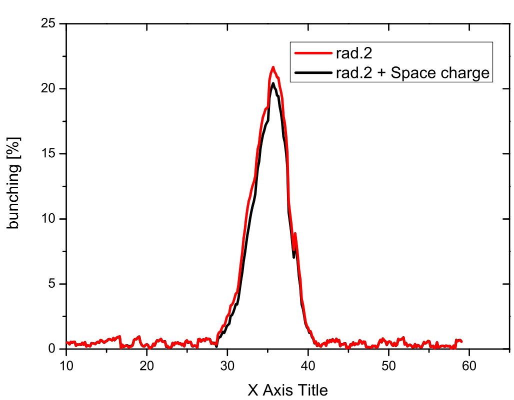

Figure 4: Bunching at the entrance of the radiator of the second stage of STARS with and without space charge force.

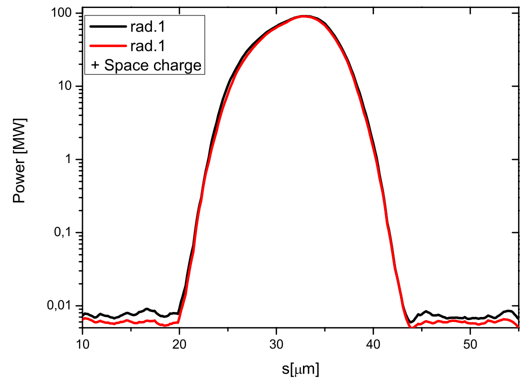

Figure 5: The radiation output of the first stage of STARS with and without space charge forces.

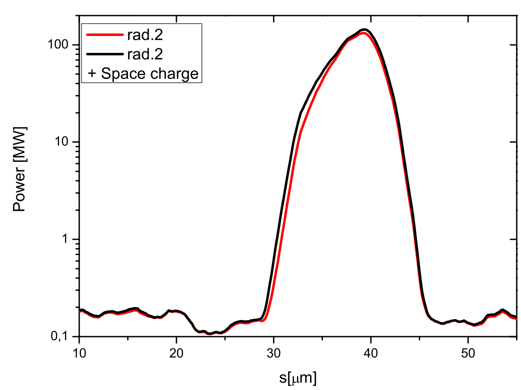

Figure 6: The radiation output of the second stage of STARS with and without space charge forces

first stage are each 2 m long. Obviously in this configuration an open radiator module leads to an almost total loss of bunching at the entrance of the second module.

However by a proper adjustment of the dispersive chicane, the effect of the longitudinal space charge force can be dramatically reduced. The strength of the dipole chicane can be chosen such that the maximum bunching is not achieved at the entrance of first module but at the entrance of the second radiator module, as shown in fig.3.

Although there is a remarkable reduction of the space charge effects on the bunching, due to the proper adjustment of the dispersive section, there remains still an small loss on bunching as shown in fig. 4.

Nevertheless, this effect is tolerable as the comparison between the radiator output with and without the effect of longitudinal space charge shows, see figures 5,6.

CONCLUSION

We investigate the FEL output degradation due to the longitudinal space charge, for STARS. The STARS concept of adjusting the radiator length by opening the gap of individual undulator modules remains valid, as the effect of the longitudinal space charge can be counteracted by a proper chose of the dispersion strength. The variation of the transverse beam dimensions under the influence of the space charge forces, are neglected, as they are assumed to be very small. This should be verified in future studies.

REFERENCES

[1] The STARS Design Group, ”STARS - Proposal for the Construction of a Cascaded HGHG-FEL”, BESSY Internal Report, Berlin, October 2006.

[2] The BESSY Soft X-ray Free Electron Laser, Technical Design Report March 2004, eds.: D. Krämer, E. Jaeschke, W. Eberhardt, ISBN 3-9809534-08, BESSY, Berlin (2004).

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

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

[5] J. Wu, ”Coherent X-ray production by cascading stages of a high-gain harmonic generation free electron laser,” Theses,May 2002

[6] S. Reiche, ”GENESIS 1.3: A Full 3D Time Dependent FEL Simulation Code”, Nuclear Instruments and Methods A429 (1999) p. 243.

[7] G. Geloni, E. L. Saldin, E. A. Schneidmiller, M.V. Yurkov, “Theory of space-charge waves on gradient-profile relativistic electron beam: An analysis in propagating eigenmodes”, NIM A 554 (2004) 20-48.

[8] J. Rosenzweig, C. Pellegrini, L. Serafini, C. Ternienden, G. Travish, “Space-charge oscillations in a self-modulated electron beam in multi-undulator free-electron Lasers”, TESLA FEL-Report 1996-15.

[9] Z. Huang, T. Shaftan, “Impact of beam energy modulation on rf zero-phasing microbunch measurements”, NIM A 528(2004) 345-349