ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB114

FEL PERFORMANCE AND BEAM QUALITY ASSESSMENT OF UNDULATOR LINE FOR THE CompactLight FACILITY

H. M. Castaneda Cortes*, D. J. Dunning, N. Thompson
UK-Research and Innovation, STFC, Cockcroft Institute, ASTeC,
Daresbury Laboratory, Daresbury, United Kingdom

Abstract

The H2020 CompactLight Project aims for the design of innovative, cost-effective, compact FEL facilities to generate higher peak brilliance radiation in the soft and hard X-ray. In this paper we assess via simulation studies the performance of a variably polarising APPLE-X afterburner positioned downstream of a helical Super Conducting Undulator (SCU). We discuss the optimum balance between the active SCU length and the afterburner length, considering the peak brilliance and pulse energy of the output. Our studies are complemented with analysis of the optical beam quality of the afterburner output to determine the design constraints of the photon beamline that delivers the FEL output to the experimental areas.

INTRODUCTION

The H2020 CompactLight project has as its main goal the design of next generation light sources, challenging the current available technology with cutting-edge ideas, aiming at the needs for a more compact design and lower operation costs [1]. Following the feedback by users to generate competitive FEL figures of merit compared to existing facilities [2], the project chose a baseline design for the undulator line comprised by a helical Super Conductive Undulator (SCU) (due to its compactness and its high efficiency to generate pulses in soft and hard x-rays) followed by a variably polarising APPLE-X afterburner (to manipulate the polarisation at the end of the line) [3], similar to the scheme proposed by Schneidmiller and Yurkov [4]. In the scheme, the main undulator induces microbunching on the electron beam on its way to the afterburner, while the FEL radiation from the main undulator is inhibited and the degree of polarisation obtained at the end of the line is perfect. The scheme was successfully demonstrated at LCLS [5] with the introduction of a corrector between the main undulator and the afterburner to divert the coherent radiation from the trajectory of the electron beam going to the afterburner.

An earlier study carried out by the CompactLight collaboration assessed the FEL performance of the undulator baseline design and its optimum configuration to fulfil the goal of compactness of the facility [6]. Since then, a more refined set of beam and undulator parameters of operation have been agreed in accordance to the design choices. This paper summarises the outcome of the study with these new parameters, doing comparisons in terms of the FEL figures of merit. A more extensive discussion can be found in [3]. In addition, an analysis of the beam quality obtained from the radiation at the end of the optimal afterburner configuration to generate vertical polarised radiation was performed, following the formalism described in [7, 8].

ASSESSMENT OF FEL PERFORMANCE

The FEL performance of the baseline design in terms of the chosen FEL figures of merit (peak brilliance, total length of the undulator line and pulse energy at the end of the afterburner) are compared to alternative undulator lines built from helical SCU and APPLE-X devices set up to generate variably polarised FEL output. The optimisation of the undulator line was studied in the soft x-rays at 250 eV and in the hard x-rays at 12 keV.

The parameters that characterise the CompactLight undulator lines for generation of SXR and HXR and the electron beam are listed in Tables 1 and 2. In Table 1, l_{section} is the length of the undulator section, a_w is the undulator parameter and λ_u is the undulator period. The APPLE-X undulator has been set up in its configuration to generate vertically linear polarised pulses. Time dependent simulations using GENESIS v1.3 [9] were carried out to assess the FEL properties of the generated pulses in SXR and HXR.

Table 1: Undulator Parameters Defined for SCU and APPLE-X Undulator

Undulator Type	**a_w**		**$_u$**	**l_{section}**
	SXR	**HXR**		
Helical SCU	2.42	0.91	13 mm	2.27 m
APPLE-X	1.93	0.507	19 mm	2.28 m

Table 2: Electron Beam and Radiation Parameters

Electron Beam Parameter	**SXR**	**HXR**
Beam Energy (GeV)	1.54	5.5
Peak Current (kA)	5	
Normalised $_{x,y}$ (mm-mrad)	0.2	
RMS slice energy spread	0.04%	0.01%
Charge (pC)	75	
Current distribution	Flat-top	
Photon Energy (eV)	250	12000

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[*] hector.castaneda@stfc.ac.uk

FEL Performance for Generation of Hard X-Rays

The results in the HXR, at12 keV resonant photon energy, are summarised in Fig. 1 which shows the pulse energy and peak brilliance along the baseline undulator line compared to the ones obtained along the SCU and APPLE-X undulator lines. The number of sections of the SCU (6 sections) has been optimised such that the level of microbunching induced by the passing of the electrons through the undulator is enough to create an initial burst of coherent radiation without the associated energy spread growth to affect the FEL interaction within the afterburner.

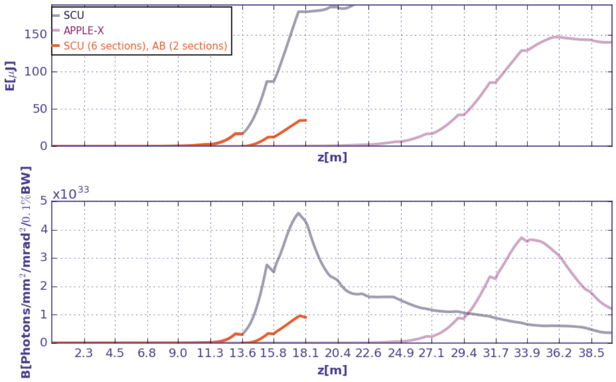

Figure 1: HXR: Comparison of 12 keV pulse energy (top) and peak brilliance (bottom) for three different scenarios: an SCU, an APPLE-X in vertically planar configuration, and the baseline SCU and APPLE-X configuration. The tick marks and labels on the z-axis correspond to the locations of the ends of individual undulator modules.

In terms of FEL performance, it can be seen that the peak brilliance obtained at the end of the baseline undulator line is 9 $\times 10^{32}$ photons/s/mm^2/mrad^2/0.1%bw, which corresponds to 25 % of the highest peak brilliance generated by the APPLE-X undulator (3×10^{33} photons/s/mm^2/mrad^2/0.1%bw). This configuration generates a pulse energy of 35 µJ, which is around 26% of the pulse energy at highest peak brilliance obtained from the APPLE-X undulator. Adding another afterburner module increases the pulse energy to 50 µJ. It should be noted that the baseline design can operate the FEL at much higher energies, up to 16 keV for SCU operation. To cover the desired spectral range, the afterburner can only generate variable polarising radiation up to 12 keV without any meaningful impact on FEL performance due to weak undulator parameters.

The trade-off in the design comes in terms of compactness. In the HXR baseline, the SCU extends to 13.6 m and the two modules of the SASE line of APPLE-X afterburner are from 13.6 m to 18.1 m, as seen in Fig. 1. The setup with two afterburner modules (which provides the highest peak brilliance at the end of the undulator line) is around half of the length that it takes for the APPLE-X to reach its highest peak brilliance, showing it to be significantly more compact. Although there is a compromise in terms of FEL performance as explained before, the compactness of the undulator line is showcased as one of the advantages of the baseline design of the prospective facility.

FEL Performance to Generate Soft X-Rays

Following the analysis performed for HXR, the FEL performance of the baseline design was assessed in the SXR domain for 250 eV photon energy (Fig. 2). It can be seen that at this photon energy only a single SCU module and a single afterburner module are required to obtain the maximum peak brilliance of 6 $\times 10^{31}$ photons/s/mm^2/mrad^2/0.1%bw and a pulse energy of 230 µJ. Using a second afterburner module does not increase the peak brilliance but increases the pulse energy to 260 µJ. Given that the highest peak brilliance and the corresponding pulse energy obtained from the APPLE-X stand-alone undulator line are 10^{32} photons/s/mm^2/mrad^2/0.1%bw and 450 µJ, the FEL performance of the baseline design of the CompactLight facility in terms of peak brilliance is 55% of the highest peak brilliance obtained from the APPLE-X. The compromise in FEL performance is not as dramatic as it was found to be for the generation of HXR.

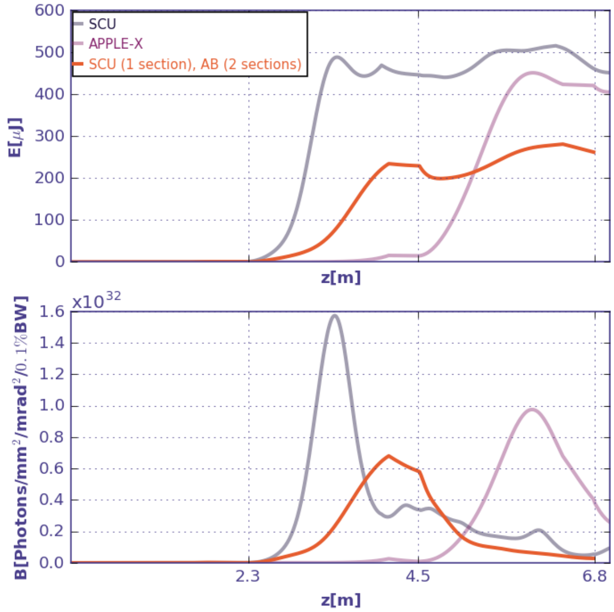

Figure 2: : SXR: Comparison of 250 eV pulse energy (top) and peak brilliance (bottom) for three different scenarios: an SCU, an APPLE-X in vertically planar configuration and the baseline SCU and APPLE-X configuration.

In terms of compactness, the baseline design with 1 section of afterburner and 1 SCU section is around 21% shorter than an undulator line comprised by a stand-alone APPLE-X tune to generate its maximum peak brilliance at the resonance photon energy.

BEAM QUALITY ANALYSIS FOR HXR

An M^2 analysis was carried out in order to find the beam quality of the optical beam generated at the end of the undulator baseline design when it is tuned to generate pulses with 12 keV photon energy. This study is fundamental in the further design of the optical beam lines to transport the pulses to the user stations. The M^2 analysis performs an expansion of the second moment of the optical beam, following a quadratic free-space propagation rule in terms of the distance of propagation z [10]

$$\sigma_i^2 = \sigma_{i_0}^2 + \left(\frac{M_i^2 \lambda}{4\pi\sigma_{i_0}}\right)^2 (z - z_0)^2, \quad \text{where i =x, y.} \qquad (1)$$

The M^2 parameter compares the beam quality of the propagated beam to the free-space propagation of a TEM_{00} Gaussian beam ($M_i^2 = 1$) [7, 8]. The rms size at the beam waist (measured from the end of the undulator) is σ_{i_0} and z_0 the waist position. M_i^2, σ_{i_0} and z_0 can be calculated from fitting the evolution of the optical beam profile (defined as $\sigma_i^2(z) = C_2 z^2 + C_1 z + C_0$) to the measured values of second moments [7, 8],

$$M_i^2 = \frac{2\pi}{\lambda}\sqrt{4C_0C_2 - C_1^2},\ z_0 = -\frac{C_1}{2C_2},\ \sigma_{i_0} = \sqrt{C_0 - \frac{C_1^2}{4C_2}}. \qquad (2)$$

The optical code OPC [11] was used to perform the free-space propagation of the pulse at the end of the afterburner and at the end of the helical SCU and APPLE-X undulators, for comparison. Time-dependent FEL simulations were performed using GENESIS 1.3 [9]. The calculated rms of the optical beams propagated in free space from the end of the afterburner are shown in Fig. 3. The beam quality parameters obtained for the pulses generated at the end of the afterburner, the helical SCU and the APPLE-X undulator lines are listed on Table 3, following the definitions in Eq. (2).

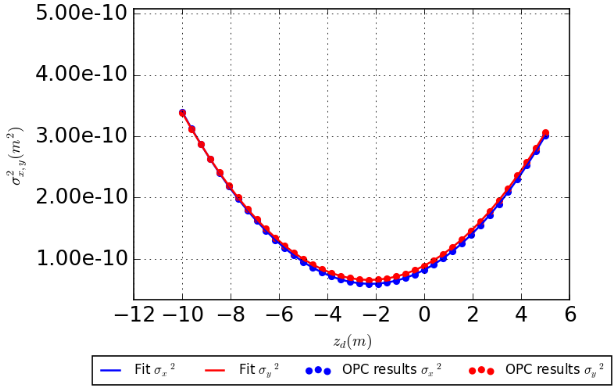

Figure 3: Rms of the optical beam as a function of the propagating distance z for the optical pulse at the end of the afterburner when the baseline design is tuned to generate photon energy of 12 keV. The continuous line shows the fit which is necessary to find the beam quality coefficients in Eq. (2).

The pulses at the end of the afterburner (with 2 sections) show to have an improved M^2 in x and y with respect to the beam quality of the pulses obtained at the end of the APPLE-X stand-alone undulator (relative differences of 4% and 9% respectively). Thereby, the baseline design using the afterburner improves slightly the beam quality of the optical beam in order to be transported down the optical beam line, rather than deteriorate it.

Table 3: Comparison between Optical Beam Parameters obtained for the Baseline Design of CompactLight, the Helical SCU and APPLE-X Undulator Lines as Stand-alone

Parameter	**SCU**		**APPLE-X**		**SCU+AB**	
	x	**y**	**x**	**y**	**x**	**y**
$\mathbf{M^2}$	2.27	2.36	2.23	2.19	2.01	2.1
$\mathbf{z_0}$ (m)	-2.19	-2.10	-3.38	-3.44	-2.22	-2.26
σ_{z_0} (µm)	8.96	9.07	10.39	10.02	7.65	8.092

SUMMARY

The baseline configuration of a helical SCU followed by two modules of APPLE-X afterburner is a significantly more compact solution for the production of variably polarised FEL output in the HXR and provides comparable beam quality than setting up a variably polarising APPLE-X undulator line. There is a trade-off between compactness and FEL performance. It should be noted that the baseline design is adaptable and allows a crossed undulator configuration with a fast electromagnetic phase shifter between the two modules to control the polarisation state of the output [3].

ACKNOWLEDGEMENTS

CompactLight has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 777431.

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