Undulators and Light Production with the XLS-CompactLight Design Study

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(Dated: February 17, 2022)

Abstract

Free Electron Laser (FEL) facilities provide broadly tunable and highly coherent photon beams. These machines still have un unexplored potential and development. The XLS-CompactLight design aims at a flexible Hard plus Soft X-ray FEL facility exploiting the latest concepts in terms of short period magnetic undulators, paving the road towards more compact photon sources.

PACS numbers: 41.60.Cr; 07.85.m

Keywords: free-electron laser; undulator magnet

I. INTRODUCTION

Over the last decades, particle accelerators developed into powerful and widely used tools for basic research, medicine and industry. When moving in a curved path, charged particles lose energy emitting synchrotron radiation: an intrinsic limiting factor to accelerate electrons at high energy that turned to have an increasingly important role in many areas of basic and applied sciences. It provides high intensity flux of photons on a broad band of frequencies, which cannot be covered with other conventional laser sources. The Free Electron Laser (FEL) exploits an ultra-relativistic electron bunch passing through the spatially periodic magnetic field of an undulator. Here, the kinetic energy of a high quality electron beam is transformed into a brilliant and short pulse laser source [1, 2] by interacting the bunch with the optical field inside a long undulator. For an FEL facility, space requirements, power consumption and main costs are driven by the linac that accelerates the electron beam. Most of the existing machines use S-band linear accelerators, not optimal a technology even though consolidated through many years of use. A higher frequency accelerating structure can achieve higher gradients and lower power requirements than those of lower frequency

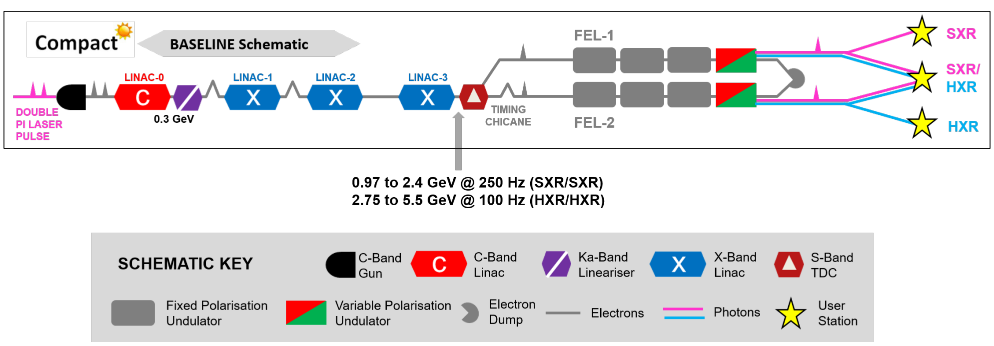

FIG. 1. Baseline schematic layout.

structures, at similar accelerating fields. The use of X-band technology further improves the situation and is expected to reduce the required length of the accelerator and associated infrastructure compared to the currently operating facilities.

II. THE XLS-COMPACTLIGHT PROJECT

The XLS-CompactLight Design Study enables the use of the X-band accelerator technology, developed for the most advanced particle accelerators of the future. High frequency X-band structures can also run at low gradients and high repetition rate (kHz regime), enabling new operational scenarios for high repetition rate X-ray FELs, currently in great demand for applications [3]. Two cases are picked: chemical properties of materials through fast magnetic dynamics studied by means of switchable FEL polarization [4]; coherent diffraction imaging of biological samples where 3D images are obtained processing several X-ray patterns, an ideal technique to reconstruct images of viruses in their native environment [5, 6]. The project objective is the design of a 5.5 GeV beam energy X-band Linac, based on the CLIC technology, to drive an FEL facility with Soft (SXR) and Hard X-ray (HXR) options. Figure 1 shows the baseline XLS layout. The main stress is on the size reduction of the facility by deploying the most advanced concepts of high brightness electron photoinjectors, very high gradient accelerating structures, and on top of that novel short period undulators, enabling to cover the HXR realm of experiments at a lower beam energy. The expected

TABLE I. Requirements on the FEL parameters.

Parameter	Unit	SXR FEL	HXR FEL
Photon energy	keV	0.25-2	2-16
Repetition rate	Hz	10^2-10^3	10^2
Two-color separation	%	20	10

FEL performance is summarized on Table I. In addition, pulse energy of hundreds of μJ and duration in the 0.1-50 fs range are required for both regimes.

III. MAGNETIC UNDULATORS

In an FEL, electromagnetic radiation is emitted by wiggling the electrons through a sinusoidal path subject to the periodic magnetic field of the undulator, specified by the undulator period λ_u and the deflection strength parameter K. These quantities define λ_R:

$$\text{resonant wavelength } \lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right), \quad K = \frac{eB_0\lambda_u}{2\pi m_e c} \tag{1}$$

where γ is the beam energy Lorentz factor, $a_u = K/\sqrt{2}\,(a_u = K)$ for planar (helical) undulators, B_0 is the peak magnetic field value, and e, m_e and c are the electron charge, the electron mass and the speed of light, respectively. Several undulator configurations have been scrutinized and compared on the basis of technology readiness and FEL performance, as well as cost and risk considerations. The undulator technology comparison is based on the highest values for the pulse energy and on the shortest length by which the optimum (saturation) FEL power is reached at the end of the exponential growth: the saturation length. In particular, the following technologies are reviewed [7]:

- permanent magnet undulator – both out-of-vacuum and room temperature or cryogenic in-vacuum devices (*e.g.* Advanced Planar Polarized Light Emitter, APPLE);
- superconducting undulator (SCU) – low temperature NbTi and Nb_3Sn structures as well as high temperature wound tapes and bulk structures.

The field scaling parameterization is derived for each undulator type, material or technology, for both planar and helical (where it applies) configurations. Full 3D FEL simulations

TABLE II. Summary of the main undulator parameters.

	Main Undulator	**Afterburner**
Technology	NbTi Superconducting	APPLE-X
Polarization	Helical	Variable
Period length	13 mm	19 mm
Maximum a_u	1.33	1.80
Beam gap	4.2 mm	5 mm
Module length	1.75 m	1.75 m

performed with the XLS electron beam parameters show that SCUs provide larger magnetic field at the same gap and period, namely the same short wavelength is covered with higher K strength and pulse energy. High temperature superconducting devices are neither mature nor cost effective enough at this stage to be considered for a user facility. The choice for the main radiator is a NbTi helical superconducting undulator. In order to perform a selectable polarization, the adopted solution is to use an APPLE-X [8] afterburner section after the main radiator since it is less expensive than having the full variable polarization undulator line, and more efficient than the crossed undulator technique resulting in a low degree of polarization. Table II shows the main parameter values of the undulator lines.

IV. FEL LIGHT PRODUCTION

The time-dependent simulation [9] with the `Genesis1.3` code [10] is carried assuming the undulator baseline design: a helical SCU followed by an APPLE-X, with appropriate propagation of the microbunched electron beam. An alternative scenario consisting of the

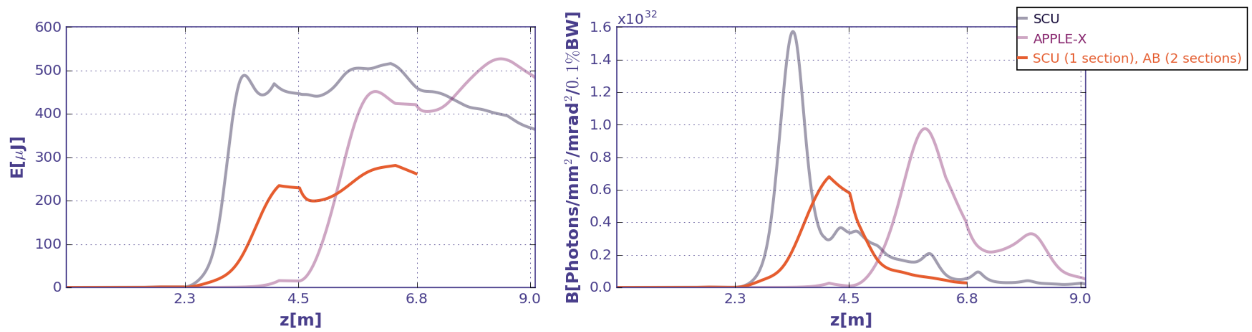

FIG. 2. Comparison of pulse energy (left) and peak brightness (right) for three different scenarios: SCU only, APPLE-X only with vertical linear polarization, and the XLS baseline configuration.

whole undulator line made only by APPLE-X devices is studied for a comparison. Figure 2 shows pulse energy and peak brightness distributions for the SCU only, APPLE-X only and XLS baseline configurations, tuned to yield FEL light at 250 eV photon energy. From the left panel: the XLS baseline has a growth shorter by $\sim 40\%$ than APPLE-X only and longer by $\sim 13\%$ than SCU only, which brings no variable polarization. Detailed optimization studies targeting also the HXR photon energy range, show that a second APPLE-X module is definitely needed to meet the XLS users' requirements on pulse energy and brightness.

V. CONCLUDING REMARKS

The XLS-CompactLight offers challenging FEL schemes such for example the simultaneous operation of HXR and SXR lines at 100 Hz, or SXR up to 1 kHz, by means of affordable and compact X-band technology. A thorough and comprehensive analysis selected NbTi superconducting undulators as the technology for the main radiator sections, as a result of the comparison based on FEL performance and technology readiness. Full start-2-end 3D simulations embedded with effects degrading the beam quality proved that target pulse energy and peak brightness are within reach, in such a compact X-ray FEL source facility.

ACKNOWLEDGMENTS

This work has received funding by the European Unions Horizon2020 research and innovation program under Grant Agreement No. 777431.

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