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THE CompactLight DESIGN STUDY

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Abstract

CompactLight (XLS) is an H2020 Design Study funded by the European Union under grant agreement No. 777431 and carried out by an international collaboration of 23 international laboratories and academic institutions, three private companies, and five third parties. The project, which started in January 2018 with a duration of 48 months, aimed to design an innovative, compact, and cost-effective hard X-ray FEL facility complemented by a soft X-ray source. In December 2021, the Conceptual Design Report was completed. The result is an accelerator that can be operated at up to 1 kHz pulse repetition rate, beyond today's state of the art, using the latest concepts for high brightness electron photoinjectors, very high gradient accelerating structures in X-band, and novel short-period undulators. This paper gives an overview of the current status, focusing particularly on the technological challenges addressed and their future applications to compact accelerator-based facilities.

INTRODUCTION

Synchrotron Radiation is a fundamental and indispensable research tool in a broad spectrum of scientific and technological fields and their applications, including materials science, condensed-matter physics, atomic and molecular physics, life science and medicine, chemistry, and environmental sciences. For this reason, the use of synchrotron radiation has increased tremendously in the last decades, as testified by the number of synchrotron light sources built to serve increasingly large users communities across many scientific and engineering disciplines.

he CompactLight project aimed to design an innovative, compact, cost-effective Hard X-Ray (HXR) FEL facility complemented by a Soft X-Ray (SXR) source. The FEL specifications that drove the design were based on the demands of potential users, considering the photon characteristics required by their current and future experiments. XLS used the latest concepts for high brightness electron photoinjectors, very high gradient X-band accelerating structures based on CLIC technology developed at CERN [1], and novel short-period super-conducting undulators. The result is a normal-conducting accelerator that can be operated at up to a 1 kHz repetition rate, well beyond today's state of the art.

The design presented in the Conceptual Design Report (CDR) [2] includes a facility baseline layout and two main upgrades, with the most advanced option allowing the simultaneous operation of both FEL beamlines, in SXR/HXR pump-probe configuration, at 100 Hz repetition rate. Figure 1 shows a schematic layout of the CompactLight facility Upgrade II.

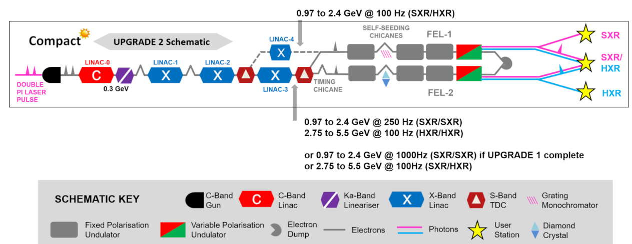

Figure 1: Schematic layout of the CompactLight facility including Upgrade II.

Compared to existing facilities with the same operating wavelengths, the technical solutions adopted by CompactLight allow the proposed facility to operate with a lower electron beam energy on a significantly smaller footprint. These enhancements make the facility more attractive and more affordable to build and operate. Figure 2 shows a 3D view of the different subsystems and their estimated lengths. The total length of the facility is just below 485 m, which is more than 250 m less than the total length of SwissFEL, for example.

The CompactLight CDR also includes preliminary evaluations of a soft X-ray FEL and an extremely compact and relatively inexpensive photon source based on Inverse Compton Scattering (ICS) using CompactLight technology. Compared with the entire CompactLight facility, this soft X-ray FEL can be considered quite an affordable solution in terms of cost and complexity, in case of limited funding capabilities. In addition, the ICS source, with its wide range of applications, is very attractive and could be easily installed and operated on university campuses, small laboratories, and hospitals.

FEL PERFORMANCE

The main features of CompactLight have been based on the users' requests and include: High FEL stability in pulse energy and pulse duration; FEL synchronization better than 10 fs; photon pulse duration less than 50 fs; a repetition rate from 1 Hz up to 1 kHz; FEL pump-probe capabilities with a large photon energy difference; small focused spot size; variable polarization, linear and elliptical; tunability up to higher photon energies; two-bunch operation and two-colour pulse generation.

Based on these requirements, CompactLight has been designed as a hard X-ray facility covering the wavelength range from 0.08 nm to 5 nm with two separate FEL beamlines:

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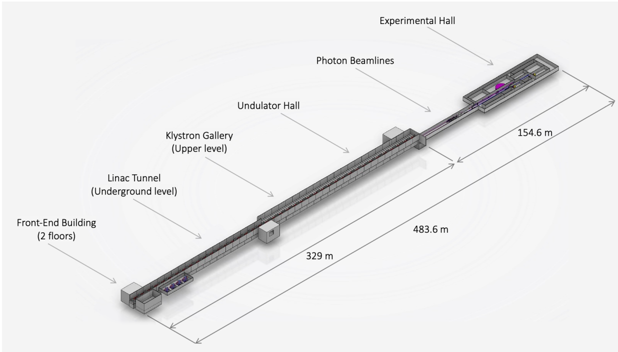

Figure 2: The planned facility allows the production of X-rays up to 16 keV in less than 485 m of length including the experimental hall.

i) A soft X-ray (SXR) FEL able to deliver photons from 5.0 nm to 0.6 nm operating up to 1 kHz repetition rate (high rep rate);

ii) A hard X-ray FEL source (HXR) ranging from 0.6 nm to 0.08 nm with a maximum repetition rate of 100 Hz (low rep rate).

Key elements proposed in the design are the dual-bunch photoinjector and the two-beam deflectors adopted for the linac. Both give huge flexibility for the facility operation, with different combinations of SXR and HXR operating modes, at high and low repetition rates.

Table 1 reports the CompactLight FEL parameters required by the users.

Table 1: CompactLight FEL Radiation Main Parameters

Parameter	Unit	SXR	HXR
Photon energy	keV	0.25 – 2	2 – 16
Wavelength	nm	5.0 – 0.6	0.6 – 0.08
Repetition rate	Hz	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	
Two-pulse delay	fs	±100	
Two-colour separation	%	20	10
Synchronization	fs	<10	

MAIN TECHNOLOGICAL BREAKTHROUGHS

While aiming to design a complete FEL facility, CompactLight has been structured as an "accelerator toolbox", in which the different subsystems could be used *stand-alone* in other accelerator-based applications, for instance, future high-energy colliders, compact linacs for medical applications, compact Inverse-Compton scattering sources, and drivers for plasma modules.

Several technological breakthroughs were achieved during the design of each CompactLight subsystem. We present here the main ones.

The Electron Source

We have designed an innovative C-band photoinjector for the electron source, with an operating gradient up to 180 MV/m. The injector gun can deliver two 75 pC e-bunches per RF pulse with less than 0.2 mm mrad normalized emittance. The gun is followed by the C-band booster linac, accelerating the electron bunches to 300 MeV energy, to the first bunch compressing chicane. The total length of the installation is less than 25 m.

The Beam Linearizer

The development of very high-frequency linearizers is of broad importance for accelerators which require short bunches, including high-frequency RF and plasma accelerators. For the XLS longitudinal phase space linearization, we have designed a Ka-band system operating at 36 GHz. The Ka-band system is based on a 30 cm long travelling-wave structure, powered by a 3 MW of RF power, and operating with an integrated voltage of 12.7 MV. We identified two possible options for the RF source: a High Order Mode Multi-Beam Klystron (HOM MBK) and a Gyro-Klystron.

The Sub-harmonic Deflecting System

An S-band (3 GHz) sub-harmonic deflecting structure, operated in the TM110 mode, has been designed to separate the two bunches before the injection into a septum magnet, which sends them into the two FEL lines. The spacing between the two bunches, 6 or 10 X-band RF cycles, is 1.5 or 2.5 RF cycles at S-band. Thus, the two bunches can be placed at the crest and trough of the RF cycle of the sub-harmonic deflector so that the kicks applied to the two bunches are in opposite directions and the separation is maximized for a given kick voltage.

The Linac Module

A baseline main linac RF module was designed to fulfill the beam dynamics requirements in all operating modes, including two-bunch operation, multi-energy, and multi-repetition rate operation. The linac module consists of a single RF source that can run in dual mode: high-energy at repetition rates of 100 Hz and low-energy at 250 Hz. Two upgrade scenarios are foreseen for the RF system. In Upgrade I the same klystron can be used with higher repetition rate, 250 Hz, for providing up to 2 GeV for photon production. For Upgrade II, shown in Fig. 1, a second klystron, with 10 MW output power and a 1 kHz repetition rate, is added and connected to the waveguide system via a high-power switch, shown in Fig. 3. Table 2 shows a summary of the nominal electron beam parameters.

The Undulator Chain

In the CompactLight design the same undulator line is used in both the soft X-ray and the hard X-ray FEL lines. Particular care has been taken to ensure that the undulator parameters are chosen appropriately to balance the output performance equally between the SXR and the HXR.

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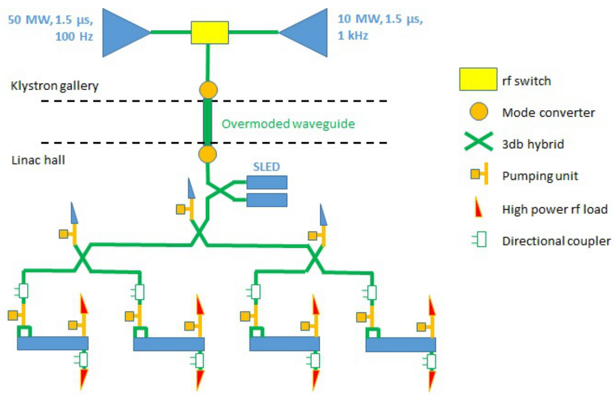

Figure 3: Sketch of the main linac RF module.

Table 2: Nominal Electron Bunch Main Parameters

Parameter	Unit	Value
Bunch Profile		Gaussian
Energy	GeV	5.5
Peak Current	kA	5.0
Normalised Emittance	mm-mrad	0.2
RMS Energy Spread	keV	550 (0.01%)
Bunch Charge	pC	75

This feature allows the facility to be more compact and cost-effective. The undulator chain foresees an innovative helical superconducting undulator, with 13 mm period and 4.2 mm gap followed by an APPLE X afterburner with 19 mm period and 5 mm gap. The length of each module is 1.75 m. Figure 4 shows the achieved pulse energy growth, pulse profiles, and spectra for HXR FEL operation.

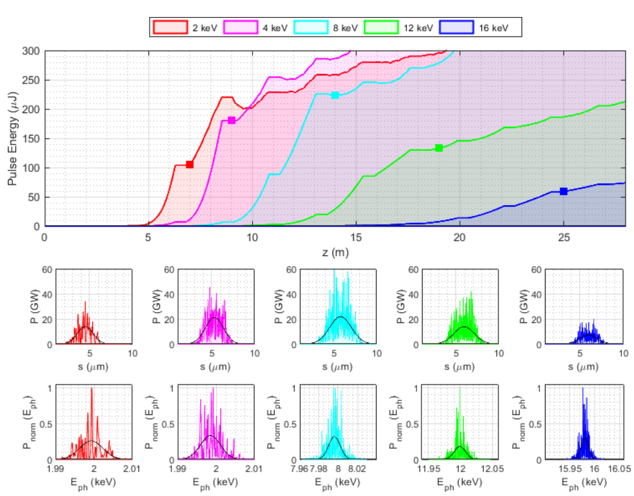

Figure 4: Pulse energy growth, pulse profiles and spectra for HXR FEL operation using the nominal bunch.

COMPACT FACILITIES

The CompactLight collaboration considered two compact facilities to further reduce the costs; a compact SXR FEL, and an Inverse-Compton Scattering (ICS) X-ray source.

Compact Soft-X-ray facility

The facility design is a simplified version of the Baseline configuration, reduced to the essential components for 100 Hz SXR output over the photon energy range 0.25–2.0 keV from a single FEL. A schematic layout is shown in Fig 5. Note that, compared to the Baseline configuration, the facility is substantially more compact: its linac is 160 m long, nearly 40% shorter than the baseline for HXR production.

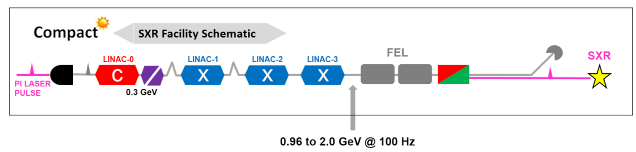

Figure 5: Schematic layout of the SXR facility. The linac length is nearly 40% shorter than for HXR production.

Inverse-Compton Scattering Source

The CompactLight technology, based on X-band high-gradient normal-conducting RF combined with high-rep-rate, low-emittance injectors, has the potential to provide both high fluxes and high brilliance. Figure 6 short a schematic layout of a hypothetical ICS source based on the previously-described subsystems.

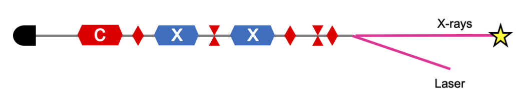

Figure 6: Schematic layout of an ICS source based on the CompactLight C-band gun and a short X-band linac.

CONCLUSIONS

The CompactLight collaboration presented the design of a high-brightness and compact hard X-ray FEL beyond today's state-of-the-art. The recently published Conceptual Design Report describes the technical concepts and the parameters used for the facility design, intending to provide a reference document for future FEL designers. It also represents an effective solution that makes X-ray FELs more affordable to construct and operate, even for small laboratories or academia with limited space and funding capabilities.

REFERENCES

[1] Eds.: P. N. Burrows *et al.*, "The compact linear e^+e^- collider (CLIC) - 2018 summary report," *CERN Yellow Reports: Monographs, vol. 2/2018*, CERN, Geneva, Switzerland, Rep. CERN-2018-005-M, 2018. doi:10.23731/CYRM-2018-002

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