

## COMPACTLIGHT DESIGN STUDY\*

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### Abstract

H2020 CompactLight Project aims at designing the next generation of compact hard X-Rays Free-Electron Lasers, relying on very high accelerating gradients and on novel undulator concepts. CompactLight intends to design a compact Hard X-ray FEL facility based on very high-gradient acceleration in the X band of frequencies, on a very bright photo injector, and on short-period/superconductive undulators to enable smaller electron beam energy. If compared to existing facilities, the proposed facility will benefit from a lower electron beam energy, due to the enhanced undulators performance, be significantly more compact, as a consequence both of the lower energy and of the high-gradient X-band structures, have lower electrical power demand and a smaller footprint. CompactLight is a consortium of 24 institutes (21 European + 3 extra Europeans), gathering the world-leading experts both in the domains of X-band acceleration and undulator design.

### MOTIVATION AND OBJECTIVES

Our aim is to facilitate the widespread development of X-ray FEL facilities across Europe and beyond, by making them more affordable to construct and operate through an optimum combination of emerging and innovative accelerator technologies. We will design a Hard X-ray FEL facility using the very latest concepts for bright electron photo injectors,

very high-gradient accelerating structures and novel short period undulators. The resulting facility will benefit from a lower electron beam energy than current facilities, due to the enhanced undulator performance, will be significantly more compact as a consequence of this lower energy as well as due to the application of very high-gradient structures, and also have a much lower electrical power consumption than current facilities through the use of an X-band RF system at 12 GHz. These ambitious but realistic aims will result in much lower construction and running costs making X-ray FELs affordable, even by national institutions or academia. We therefore anticipate that our Design Study will enable FEL facilities to proliferate across all of Europe and beyond much more rapidly than third generation light sources have managed over the past decades.

CompactLight gathers the world-leading experts in these domains, united to achieve two objectives: disseminate X-band technology as a new standard for accelerator-based facilities and advance undulators to the next generation of compact photon sources, with the aim of facilitating the widespread development of X-ray FEL facilities across and beyond Europe by making them more affordable to build and to operate.

### A COMPACT HARD X-RAY FEL

A standard layout of an FEL is shown in Fig. 1. It consists of a high-brightness electron source, a pre-acceleration section up to about 300 MeV, a laser heater, to optimize the micro-bunching instability, three linear accelerating sections (L1, L2, and L3 in the figure), and two magnetic chicanes,

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to achieve acceleration and longitudinal bunch compression before delivering the beam to the undulator lines where the photons are created. CompactLight aims at significantly reduce the footprint of the entire facility, using compact sources, a compact and power efficient rf module, and a compact undulators of the next generation. Table 1 shows the range of parameters that CompactLight sets as target for its design of the next generation hard X-ray facilities.

Table 1: Preliminary Parameters of the Proposed Compact-Light Hard X-ray Facility

Parameter	Units	Value
Linac frequency	GHz	12
Linac gradient	MV/m	70
Beam energy	GeV	< 4.6
Bunch Charge	pC	< 250
Normalized emittance	mm mrad	< 0.5
Bunch length	$\mu\text{m}$	< 8
Pulse duration	fs	< 1 to 50
Pulse repetition rate	Hz	100-1000
Number of bunches per pulse	#	1-3
FEL Parameters		
$K$ value	#	1.13
Minimum wavelength	$\text{\AA}$	1
Number of photons per pulse	#	> $10^{12}$
Pulse bandwidth	%	$\ll 0.1$

### Compact Injector Gun

Investigation into high-performance sources able to deliver high brightness, high repetition rate electron beams for the generation of high-flux, highly coherent radiation and integration with CompactLight are the main objectives of CompactLight. Currently, electron sources used in XFELs are based on three RF technologies: 1.3 GHz, 24 MV/m, superconducting L-Band; 2.86 GHz, 17 MV/m, room-temperature S-Band; and 5.7 GHz, 35 MV/m, room temperature C-Band at SACLA and SwissFEL [1]. Recent developments in high-gradient acceleration in S- and in C- bands, where accelerating voltages as high as 55 MV/m in S band have been achieved, are showing the way to a new generation of high-gradient S- band and C- band injector guns. Injectors based on high-gradient X-band, possibly equipped with a K-band linearizer running at 36 GHz, would certainly represent a leap forward toward very compact high-brilliance injectors.

Enabling a new generation of compact high-brightness electron sources will impact the whole electron accelerator-based science community, in particular photon sciences, where electron beams drive a variety of tools such as FELs, electron scattering experiments, imaging and radiation therapy.

A full X-band gun will be presented in [2]. This design is based on the a photo cathode rf gun in [1], operating at 12 GHz with a peak voltage of 200 MV. The cathode is followed

by CLIC-like X-band structures with gradient 70 MV/m, able to accelerate the beam up to 300 MeV. A preliminary phase space distribution at the rf gun exit is shown in Fig. 2. As it can be seen on Fig. 2 the beam is accelerated up to 60 MeV by 5.6 cell rf gun and single X-band structure. The projected emittance at the end of first structure is simulated as  $\epsilon = 0.4$  mm.mrad and the bunch length is  $\sigma_z \approx 680$  fs. To minimize the uncorrelated energy spread we introduce a chirp by adjusting the phase of X-band structure.

### Compact Linac Module

The linacs are composed by a sequence of modules. A module is a physical unit that includes an X-band RF distribution network and X-band accelerating structures, as well as beam diagnostic devices and focusing magnets for beam transport. The aim of the CompactLight Design Study is to determine the key parameters of an FEL facility based on X-band acceleration, including transverse focusing, mechanical stability, alignment tolerances and diagnostics, and then design, assemble and test experimentally all the RF components of such an X-band module. Preliminary studies have outlined the basic parameters of such a module; they are sketched in Fig. 3.

As the feasibility of high-gradient X-band accelerator technology has been proven, the manufacturing of X-band structures is ready to move from individual prototypes to high volume production. Industrialization of X-band components is becoming crucial for facilities and market to grow together. Efficient RF power sources also need to be developed, integrated and industrialized from this perspective. One of the main objectives of CompactLight is the definition of a standard unit for X-band based accelerators, a standardized module inclusive of RF source with optimized pulse compressor, RF distribution network, accelerating structures equipped with magnetic elements and diagnostics. This standard unit will provide a template for industrial involvement.

### Compact Undulator

In parallel to X-band developments, undulators have also made significant improvements in capability in recent years, with the promise of more to come. Two new undulator technologies have now been proven on light source facilities, cryogenic permanent magnet undulators and superconducting undulators, and both continue to improve in performance as a greater confidence and understanding in each type develops. Neither of these two new technologies has been applied to an XFEL design until now.

Reducing the required electron beam energy through the use of more advanced undulators results in additional savings roughly proportional to the energy reduction. The application of both higher frequency acceleration and advanced undulators could facilitate also the upgrade of existing facilities to higher energy, with the possibility of minimal or no increase in civil construction. Parallel to the development of compact X-band accelerator technologies, CompactLight will push the generation of coherent light beyond the current state-of-the-art, and develop innovative new technologies for

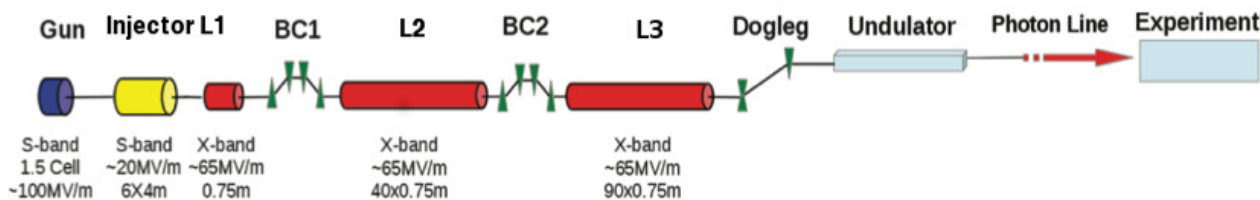


Figure 1: Layout of an FEL facility.

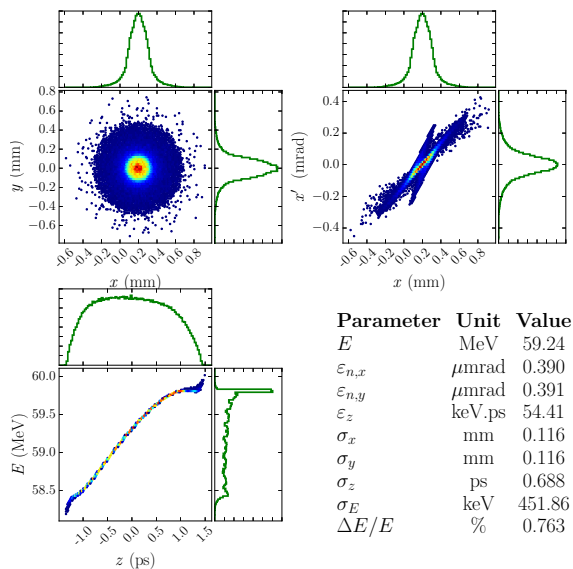


Figure 2: Transverse beam distribution (top left), and horizontal (top right) and longitudinal (bottom left) phase spaces with associated histograms representing the projection along the respective axis and beam parameters of the bunch at the exit of first X-band cavity of injector.

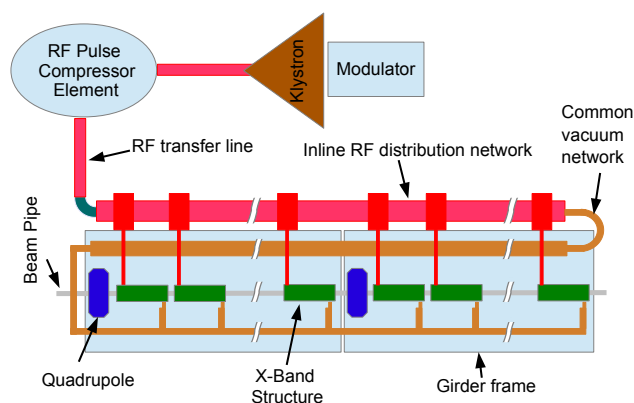


Figure 3: Schematic illustration of an X-band module.

efficient light generation that will lead to the next-generation of compact coherent light facilities, including permanent magnet, or super-conducting undulators. The potential for improving the photon generation process and the FEL operation is a rapidly developing field of research: achieving shorter saturation lengths, shaping the pulses in time and in spectrum domain, two-colour generation, seeding and harmonic lasing are some of the directions being explored.

A review of the state-of-the-art for existing technologies will be performed, together with a study of the emerging technologies, that is technologies whose examples have already proven on storage rings or FELs their potential, but are of recent conception, among these for example cryogenic permanent magnet undulators (CPMU) and superconductive undulators (SCU). Both CPMU and SCU technologies show the potential to reach for short periods while keeping high  $B$  values (40%-50% larger than standard PMU's), with the CPMU's notably less subjected to wakefield effects.

With a target beam energy of 4.6 GeV and a  $K$  parameter of 1.13, the target wavelength of  $\lambda_{\text{FEL}} \approx$  can be achieved only with undulator periods of  $\lambda_U \approx 1.2$  cm. This sets the undulator design. The target undulator performance also determines the specifications on the incoming beam, through the Pierce parameter [3]. Considering electron peak currents within reach, of the order of 2 kA, one needs to have a transverse normalized emittance less than 0.5 mm mrad, and a relative energy spread better than 0.05% in order to achieve a saturation length  $L_S \approx 50$  m.

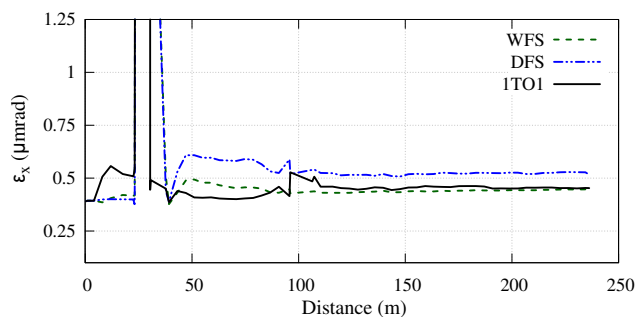


Figure 4: Emittance growth along a preliminary design of a full X-band injector and linac.

Preliminary beam dynamics simulations of the linac and bunch compressors have been performed, the result is shown in Fig. 4. The tests confirmed that sophisticated beam-based alignment techniques developed for CLIC can successfully be applied at CompactLight, allowing one to reach the required performances in terms on beam transport.

## CONCLUSIONS

A recently submitted H2020 proposal for a design study of a compact light source called CompactLight has been approved, with start date January 1st 2018. The goals of CompactLight are the design of a full-fledged free-electron laser based on the most advanced technologies for a compact

electron injector gun, an X-band based linac, and a short-period/superconductive undulator to enable smaller electron beam energy. The CompactLight consortium consists of 24 institutes (21 European + 3 extra Europeans), gathering the world-leading experts both in the domains of X-band acceleration and undulator design. World-leading experts united to achieve two objectives: disseminate X-band technology as a new standard for new accelerator-based facilities, and advance undulators to the next generation of compact photon sources, with the aim of facilitating the widespread development of X-ray FEL facilities across and beyond Europe by making them more affordable to build and to operate.

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