CompactLight DESIGN STUDY

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Abstract

The H2020 CompactLight Project aims at designing the next generation of compact X-rays Free-Electron Lasers, relying on very high gradient accelerating structures (X-band, 12 GHz), the most advanced concepts for high brightness electron photo injectors, and innovative compact short-period undulators. Compared to existing facilities, the proposed facility will benefit from a lower electron beam energy, due to the enhanced undulators performance, and will be significantly more compact, with a smaller footprint, as a consequence of the lower energy and the high-gradient X-band structures. In addition, the whole infrastructure will also have a lower electrical power demand as well as lower construction and running costs.

INTRODUCTION

Synchrotron radiation (SR) has become a fundamental and indispensable tool for studying matter. The latest generation of sources, based on Free Electron Lasers (FELs) driven by linacs, feature unprecedented performance in terms of pulse duration, brightness, and coherence. X-ray FEL facilities provide new science and technology capabilities, however their high costs and complexity have direct consequences on their diffusion: at present, only major accelerator laboratories are able to construct and operate them. On the other hand, the demand for new FEL facilities is worldwide continuously increasing, spurring plans for new dedicated machines. This has led to a general reconsideration of costs and spatial issues, particularly for hard X-ray facilities, driven by long and expensive multi-GeV normal conducting linacs. CompactLight (XLS) [1] is an International Collaboration, funded by the European Union, including 24 Partners and 5 Associated Institutes. It represents 9 EU Member States, 2 EU Associated Countries, 1 International Organization, and 2 Third Countries. The main objective of the Collaboration 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. The three-year design study, funded in the framework of the Horizon 2020 Research and Innovation Programme 2014-2017, started in January 2018, and intends to design an hard X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo-injectors, high-gradient X-band structures operating at 12

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GHz, and innovative short-period undulators. Compared with existing facilities, the proposed facility will (i) benefit from a lower electron beam energy, due to the enhanced undulator performance, (ii) be significantly more compact, as a consequence of the lower beam energy and the high gradient of the X-band structures, (iii) be more efficient (less power consumption), as a consequence of the lower energy and the use of higher frequency structures. These ambitious, but realistic aims, will make the design less expensive to build and operate when compared with the existing facilities, making X-ray FELs more affordable. Based on user-driven scientific requirements, i.e. wavelength range, beam structure, pulse duration, synchronisation to external laser, pulse energy, polarisation, etc., our objective is to provide the design of an ideal X-band driven hard X-rays FEL, including, as well, options for soft X-ray operation.

USER REQUIREMENTS AND LAYOUT

The user requirements for CompactLight have been established interacting with existing and potential FEL users in a variety of formats. We have held face-to-face discussions at several workshops and meetings since the start of the project, we have developed a questionnaire soliciting information on aspects of their potential experiments, and we have held a specific CompactLight User Meeting at CERN in November 2018. We have distilled all of these inputs into a comprehensive photon output specification [2] summarised in Tab. 1. A preliminary layout of the CompactLight facility is shown in Fig. 1. A key request from the user community, which affects the facility layout significantly, is the requirement for large wavelength separation when operating in two colour mode. This effectively means that two bunches must independently reach saturation in two different undulators. Normally it would be expected that this would happen in a very long undulator, tuned for two different wavelengths. However, we have decided to operate in parallel rather than series, which has several additional advantages. First, the total undulator length is approximately the same and so the parallel option is more compact overall; second, the two independent wavelengths could be combined into a single experiment or, if that is not required, two experiments could take place at the same time, doubling the capacity of the facility.

Table 1: Main Parameters of the CompactLight FEL

Parameter	**Unit**	**Soft X-ray**	**Hard X-ray**
Photon energy	keV	0.25 – 2.0	2.0 – 16.0
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	±100
Two-colour separation	%	20	10
Synchronization	fs	< 10	< 10

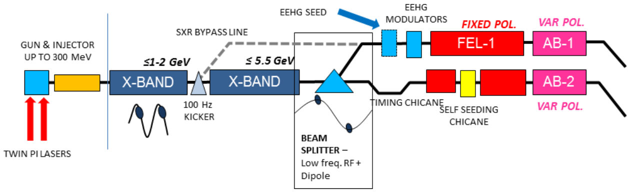

Figure 1: Sketch of the entire CompactLight facility in a two-pulse, two-color scheme.

Furthermore, we plan for the two FELs to operate over the full wavelength range. When running in hard X-ray mode the electron energy will be up to 5.5 GeV at 100Hz, in soft X-ray mode the energy will be up to 2 GeV and, since the linac gradient will be much reduced, the repetition rate will be able to be increased significantly. A repetition rate of 1000 Hz for the soft-X-ray FEL will be a unique and highly desirable feature of our facility. We recognise that this is a very challenging target for many systems, and that we might have to compromise on this ambition during the course of the Design Study. We are also considering additional concepts, which include seeding in both FELs and a bypass line at 2 GeV so that one FEL could run soft X-ray and the other hard X-ray, both at 100 Hz. Preliminary time-dependent evaluations, made with GENESIS [3] for different undulators @16 keV (3 mm gap), are summarised in Tab. 2. A conceptual design for a 36 GHz RF undulator is presented in [4].

Table 2: Results of GENESIS Time-dependent Simulations

Parameter	**CPMU**	**Delta**	**Hybrid**	**SCU**
Saturation power [GW] (pulse average)	9.1	8.9	7.6	9.8
Saturation length [m]	24.5	26.5	29.1	15.6
Sat. pulse energy [μJ]	49	48	29	54
FWHM bandwidth [10^{-3}]	0.987	0.975	0.996	1.16
Peak brightness [10^{33} × × ph/s/mm^2/mrad^2/0.1%bw]	2.39	2.37	1.98	2.18

LINAC DESIGN AND MAIN SUBSYSTEMS

As shown in Fig. 1, the linac layout consists of an injection section, up to 300 MeV, with a high-brightness electron source and a laser heater, to optimise the micro-bunching instability. The first magnetic bunch compressor (BC1) is located at 300 MeV. Two X-band linacs, downstream the injection, separated with a second bunch compressor (BC2) at an energy between 1 GeV and 2 GeV, will boost the beam energy up to 5.5 GeV. At the exit the beam is steered to different undulators with a spreader. For the electron source three photocathode RF guns operated at S-, C-, and X-band are being considered. While for the first two options an X-band cavity will be adopted to linearise the beam longitudinal bunch profile, for the X-band option we are investigating the possibility to use a lineariser operating at 36 GHz (Ka-band) [5, 6]. Moreover, for all the solutions, we are also evaluating the possibility to use RF velocity bunchers and possibly passive linearisers [7]. For the main linac our goal is to define a standardised RF unit based on the CLIC technology [8], which can be used in all the main and sub-design variants. In addition to the accelerating structures, the RF unit will include klystron, RF compressor and waveguide components as a well. This choice will greatly simplify the industrialisation process, with a considerable reduction in production costs. Preliminary RF parameters of the accelerating structure are reported in Tab. 3.

Table 3: Preliminary RF Parameters

Parameter	Unit	Value
Frequency	GHz	11.9942
Phase advance	rad	$2\pi/3$
Average iris radius $\langle a \rangle$	mm	3.5
Total length	m	0.9
RF pulse	μs	1.5
Average gradient	MV/m	65
Group velocity	%	4.5 – 1.0
Filling time	ns	140
Input power per structure	MW	9.8
Structures per module	-	4

Two operating modes have been considered: 100 Hz for hard X-ray FEL and 1 kHz for soft X-ray FEL.

PRELIMINARY SIMULATION AND BEAM PARAMETERS

Particle tracking runs of photo-injectors based on all S-band, C-band and X-band RF technology for the Gun and the following accelerating structures have been done assuming a 65 MV/m accelerating gradient in the main linac at 100 Hz repetition rate [9]. Injector optimisation studies have addressed the minimisation of the transverse normalised emittances at the expense of the bunch length. This has forced operation to a relatively low initial peak current and, eventually, to a total compression factor of approximately 100 for a final peak current of 5 kA. A two-stage magnetic compression scheme (BC1 + BC2) is adopted. Table 4 lists the main electron beam and FEL parameters for the 100 Hz rep. rate scenario. Figure 2 shows the analytical prediction for the peak voltage of a harmonic cavity in the low energy section of the linac, for linearisation of the compression process, in different injector scenarios. A design of a full C-band inejector is presented in [10]. The beam energy at the BCs and at the intermediate extraction point for the soft X-ray FEL (SX) and at the linac end for the hard X-ray FEL (HX) is constrained by the second priority requirement of SX FEL operation at 1 kHz. This is also served by the 2-stage compression, but the main linac has an accelerating gradient of approximately 20 MV/m, and the beam energy at the SX FEL is 2.5 GeV. Longitudinal geometric wakefields in the injector and in the X-band main linac sections have been calculated on the basis of a realistic 3-D inner geometry of the accelerating structures. The effect of the wakefields after the beam has reached the minimum bunch duration is important, and it translates into a residual, mostly linear, energy chirp. Still, a proper phasing of the linac sections has been adopted to simultaneously guarantee the specified total compression factor, the required beam energy at the SX and HX extraction point, and a final relative energy spread smaller than 0.1%. Simulation studies have so far foreseen 3-D space charge codes for the injector, 1-D tracking codes for the main linac, 1-D and 3-D FEL codes for the FEL, starting from the predicted beam parameters at the undulator entrance. A consistent linear optics design from the injector to the FEL is ongoing. Figure 3 shows preliminary results for the beam longitudinal phase space from an S-band injector, at the extraction point for the soft X-ray and the hard X-ray FEL. The relative rms energy spread is respectively 0.05% and 0.02%. The peak current in the bunch core is 5 kA. A first start-to-end simulation is presented in [11].

Table 4: Main Electron Beam and FEL Parameters

Parameter	Value
Max energy	5.5 GeV @100 Hz
Peak current	5 kA
Normalised emittance	0.2 mm.mrad
Bunch charge	< 100 pC
RMS slice energy spread	10^{-4}
Max photon energy	16 keV
FEL tuning range at fixed energy	×2
Peak spectral brightness @16 keV	10^{33} ph/s/mm^2/mrad^2/0.1%bw

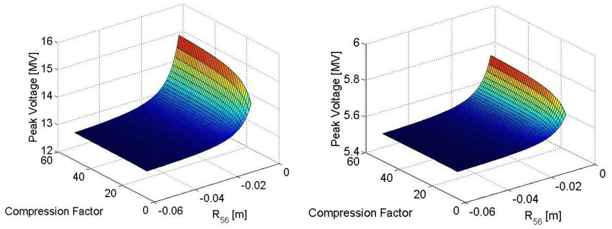

Figure 2: Peak voltage of the harmonic cavity (lineariser) as a function of momentum compaction and compression factor in BC1, for the S-band linac + X-band lineariser (left) and C-band linac + Ka-band lineariser scenario (right).

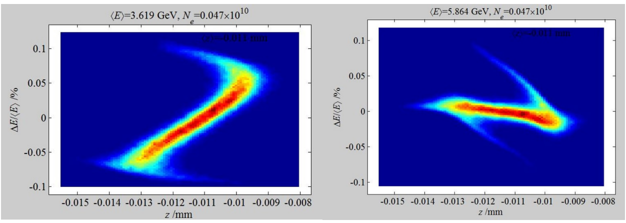

Figure 3: Longitudinal phase space from 1-D tracking run, at the exit of the linac section for the soft X-ray FEL (left), and at the end of the linac for the hard X-ray FEL.

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