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STATUS OF THE COMPACTLIGHT DESIGN STUDY*

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Abstract

CompactLight (XLS) is an International Collaboration of 24 partners and 5 third parties, funded by the European Union through the Horizon 2020 Research and Innovation Programme. The main goal of the project, which started in January 2018 with a duration of 36 months, is the design of an hard X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo-injectors, high-gradient accelerating structures, and innovative short-period undulators. The specifications of the facility and the parameters of the future FEL are driven by the demands of potential users and the associated science cases. In this paper we will give an overview on the ongoing activities and the major results achieved until now.

INTRODUCTION

The CompactLight project aims to design a hard X-ray FEL facility beyond today's state of the art, combining the latest and most innovative technologies for the major components of the FEL system, very high gradient accelerating structures at 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 have a smaller footprint due to the high gradient and will require a lower electron beam energy, owing to the enhanced undulator performance. The whole infrastructure will have lower electrical power demand, construction and operation costs. The user requirements have been identified by existing and potential FEL users via discussions at several workshops, meetings, and surveys. They are summarised in Table 1 and in [1].

Table 1: Baseline Parameters of the CompactLight FEL

Parameter	Unit	SXR	HXR
Photon Energy	keV	0.25-2.0	2.0-16.0
Repetition rate	Hz	250	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

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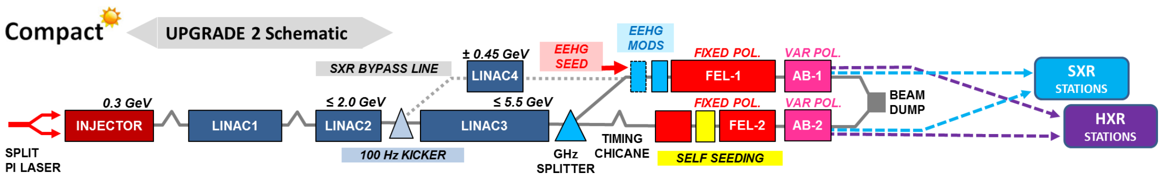

Figure 1: Schematic of CompactLight with Upgrade 2 applied.

FACILITY OVERVIEW

A key user request is double FEL pulses separated in wavelength and time. We propose to generate a double electron bunch at the photo-injector (PI) using a split and delayed PI laser pulse. Each bunch will be accelerated on a separate cycle of the RF then given a small energy separation in a short linac section operating at a sub-harmonic of the main linac. A DC magnet and septum system will then separate the two bunches and send them into two parallel undulator sections one of which may contain a electron beam delay chicane. This parallel option is more compact than using two undulators in series and allows the two FEL pulses to have independently controllable wavelength and timing separation and to be combined into a single experiment or sent to two independent experiments, doubling the capacity of the facility. Several advanced undulator technologies are being assessed [2] and it has been found that a maximum beam energy of 5.5 GeV is sufficient for a number of technologies to deliver the required FEL performance, with the final choice to be made at a later date in combination with a cost and risk analysis. The summary of electron beam parameters is shown in Table 2.

Table 2: Baseline Electron Beam Parameters

Parameter	Unit	SXR	HXR
Beam Energy	GeV	1-2	2.75-5.5
Bunch Charge	pC	75	75
Normalized Emittance	mm-mrad	0.2	0.2
Max Peak Current	kA	5	5
Min Bunch Length	fs	2	2
RMS slice energy spread	%	0.03	0.01

Both CompactLight FEL beamlines will operate over the full wavelength range. In HXR mode the electron energy will be up to 5.5 GeV at 100 Hz. In SXR mode the energy will be up to 2.0 GeV and, since the linac gradient will be reduced, it will be possible to increase the repetition rate to 250 Hz for the baseline configuration.

The baseline configuration satisfies all the essential output requirements identified by the users. Two upgrades beyond the baseline configuration are envisaged. Upgrade Option 1 will enable the SXR repetition rate to increase to 1 kHz by adding further RF klystrons. Upgrade Option 2 will add seeding to both FEL lines (currently we are investigating EEHG for FEL1 and self-seeding for FEL2) and a SXR bypass line with a extra linac section, this will allow simultaneous independent HXR/SXR output to two independent experiments. Figure 1 shows a schematic of CompactLight with Upgrade Option 2 applied.

Injector

The XLS injector must generate and accelerate the electron beam up to 300 MeV with charge, emittance, bunch length and energy spread suitable for acceleration in the X-band linac. The target injector parameters are reported in Table 3. To achieve these parameters, the injector integrates various components: the gun, the capture section to boost the energy to 300 MeV, including the possibility to operate in the velocity bunching configuration [3], the solenoids for beam emittance compensation, and higher harmonics RF structures for longitudinal phase space linearization. Different schemes have been investigated including RF gun injectors at different operating frequencies (S, C and X band) and a DC gun based design aiming to achieve the target parameters. One of the most promising injectors is the C-band one.

Table 3: Target CompactLight Injector Parameters

Parameters	Units	Value
Beam Energy	MeV	300
rms Bunch Length σ_t	fs	350
Peak current $Q/\sqrt{12}\sigma_t$	A	60
rms Energy Spread	%	0.5
Projected norm. emittance	mm-mrad	0.2
Repetition Rate	Hz	100–1000

The gun is followed by two C-band TW structures [4] and the solenoids after the gun and around the TW structures control the beam emittance increase also in case of longitudinal compression by velocity bunching. The gun, the most critical component of the injector, will operate at very high cathode peak field (>200 MV/m) and will be powered with extremely short RF pulses (<200 ns) to allow operation up to the kHz regime [4]. Different types of RF gun couplers have been studied to control the pulsed heating. They are represented in Fig. 2. The first type is a mode launcher-type [5] while the second one is a proposed new coupler that operates on the TM_{020} mode on the full cell. This permits to couple the field in the waveguide, electrically, strongly reducing the pulsed heating. The main gun parameters are reported in Table 4.

RF Systems

The CompactLight linacs, which accelerate from 300 MeV to 5.5 GeV, are based on X-band, high-gradient technology. The linac is highly modular with repeated ≈4 m long units.

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Table 4: Main Parameters of the C-Band Gun

Parameter	Unit	Value
Resonant frequency	GHz	5.712
$E_{\mathrm{cath}}/\sqrt{P_{\mathrm{diss}}}$	MV/(m.MW$^{0.5}$)	65 (55)
RF input power	MW	40 (70)
Cathode peak field	MV/m	200–240
Rep rate	Hz	100$^{(\star)}$
Filling time	ns	150
RF pulse length	ns	180
$E_{\mathrm{surf}}/E_{\mathrm{cath}}$		0.9
Pulsed heating	K	<40
Average diss. power	W	200

$^{(\star)}$ Upgrade Options 1 and 2, respectively at 250 Hz and 1 kHz rep rate, are being studied.

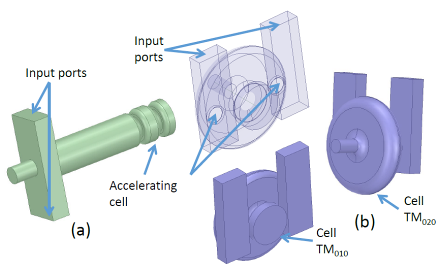

Figure 2: Proposed input couplers: (a) mode launcher type; (b) new coupler with TM_{020} cell.

Each so-called rf unit consists of a modulator, klystron pulse compressor and wave guide network which feeds four 1 m long accelerating structures. The klystron of the baseline rf unit is a 50 MW klystron running at 100 Hz. It is available commercially from CPI and is used at more than four laboratories. With an rf pulse compressor, it can deliver 44 MW to each of the four accelerating structures. The accelerating structures have an average beam aperture of 3.5 mm, which is determined in an optimization which balances short-range wakefields (large aperture) against the number of klystrons needed for the final energy (small aperture). The accelerating gradient with the 44 MW input pulse is 65 MV/m giving a total energy gain of 234 MV/rf unit.

The linac can be upgraded (Upgrade Option 1) to enable a repetition rate up to 1 kHz at 2 GeV energy operation. This is accomplished by adding a 6 MW klystron and a power switch to each rf unit. The rest of the rf unit remains the same. The 6 MW klystron is available commercially, manufactured by Canon, and is also operational at over four laboratories. In this mode the input power to each structure is 5.4 MW, the gradient is 22.7 MV/m and the total energy gain across each rf unit is 81.7 MeV.

START-TO-END (S2E) SIMULATIONS

Particle tracking runs have been done assuming a 65 MV/m accelerating gradient in the main X-Band linac at 100 Hz. Injector optimisation studies have addressed the minimisation of the transverse projected and sliced emittances. Two stage magnetic bunch compressors (BC1 + BC2) are employed to reach a peak current of 5 kA at the end of the linac. Table 2 lists the main electron beam parameters at the FEL for the 100 Hz repetition rate scenario.

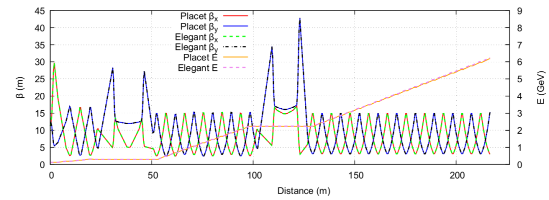

Figure 3: Beta Functions and beam energy along the linacs.

Full 6-D Tracking simulations have been performed using both Placet [6] and Elegant [7] codes. The simulation of the linac starts at 60 MeV using the distribution created by ASTRA [8]. The s2e first order optics are illustrated in Fig. 3. The final bunch distribution and its parameters are shown in Fig. 4. It is seen that the bunch is compressed down to 9 μm and the RMS energy spread of the bunch at the end of linac is 0.03%, which is acceptable for FEL generation.

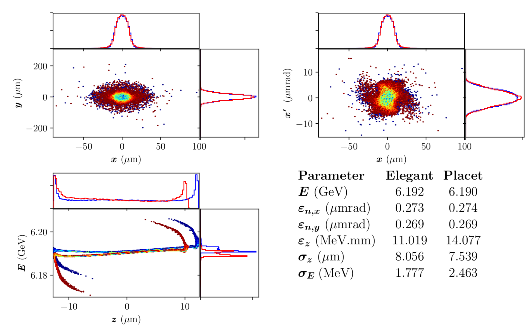

Figure 4: Beam parameters, phase spaces and transverse distribution of bunch at the end of linac with associated histograms.

To benchmark the FEL codes and semi-analytic approximations a study case has been carried out to determine the performance of a FEL tuned to 16 keV based on a cryogenic permanent magnet undulator (CPMU), one of the candidate technologies. The electron beam has a flat-top charge distribution and length 1.64 μm, which corresponds to 5kA peak current for 27 pC bunch charge. The other parameters are listed in Table 2 . The optimised average β function of 9 m minimised the gain length. Figure 5 shows the results

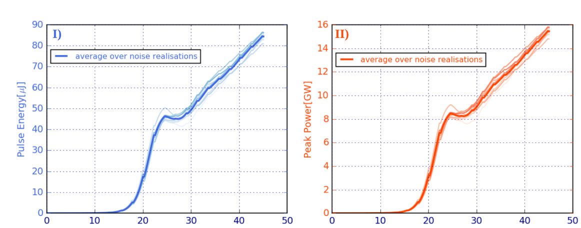

Figure 5: a) Evolution of pulse energy along the undulators, b) average of peak power over all electron beam slices.

using Genesis 1.3 [9] code. As shown, the FEL saturates at a distance of about 25 m and the peak power reaches 5 GW in SASE operation.

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