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FEL design with accelerator and undulator requirements

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On behalf of the CompactLight Partnership

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Abstract

This report describes the salient conceptual features of the CompactLight photon source, describing the machine layout and its modus operandi. The main parameters of the facility, grouped into facility sub-systems, are summarized in tables, which identify the baseline facility configuration, the proposed upgrade phases, and the technological recommendations provided by the individual work packages for its implementation. As a result, this document anticipates the CompactLight design study, and paves the way to the production of a more detailed conceptual design report.

Contents

1 Facility Concept

1.1 CompactLight FEL

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. On the one hand, their high costs and complexity has 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) 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 a hard X-ray FEL facility beyond today's state of the art, using the latest concepts of bright electron photo-injectors, high-gradient X-band structures operating at 12 GHz, and innovative short-period undulators. Compared with existing facilities, the proposed facility will (i) feature a reduced size building due to a lower electron beam energy, thanks to the enhanced undulator performance, (ii) be significantly more compact, as a consequence of the high gradient of the X-band structures, (iii) be more efficient (less power consumption), as a consequence of the lower beam energy and the use of higher frequency structures. These ambitious, yet 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-ray FEL, including, as well, options for soft X-ray operation, external seeding schemes to produce longitudinally coherent x-ray pulses and double pulse operation for FEL-pump FEL-probe experiments. Figure 1 shows the peak photon brightness targeted by CompactLight in the framework of the present short wavelength FEL facilities.

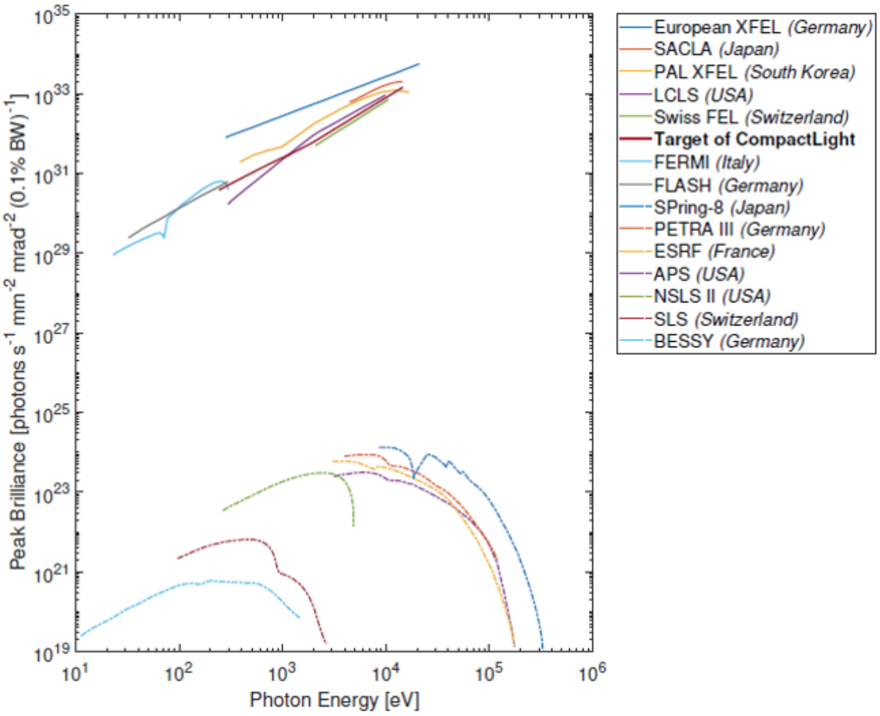


Figure 1: Peak photon brightness in short wavelength FEL facilities.

1.2 Layout

The user requirements for CompactLight have been established by interacting with existing and potential FEL users in a variety of formats [1]. We have distilled all of these inputs into a comprehensive photon output specifications, summarised in Tab. 1. Figure 2 shows the facility baseline layout and the two upgrade stages. The proposed FEL features great flexibility in order to satisfy the variety of user requirements. The FEL tuning range, and corresponding beam energy operating points, are shown in Fig. 3. This is achieved by operating the machine in different modes at each of the three presented scenarios. The obtained FEL performances are summarized in Tab 2. The common features of the three configurations are:

- twin bunches from the photo-injector sitting in near-consecutive RF buckets, separated by hundred's of ps, for the simultaneous operation of two FEL lines, thus driving either FEL-pump FEL probe experiments at a single end-station, or experiments at two distinct end-stations;
- acceleration in X-band linacs and double magnetic bunch length compression;
- emission of soft x-rays from a low energy (<2 GeV) electron beam at high repetition rate, either 250 Hz or 1 kHz, and emission of hard x-rays from high energy (> 2.8 GeV) electron beam at low repetition rate (100 Hz);
- the spectral separation of the twin pulses (either the two soft x-ray pulses or the two hard x-ray pulses) relies on the independent gap tuning of the two (identical) undulator lines, while different polarization adjustment is provided by tuning of the afterburners;
- the temporal separation of the two FEL pulses goes from perfect synchronization to ± 100 fs, at the end-station.

The baseline layout is able to generate two synchronized either soft or hard x-ray photon pulses in Self-Amplified Spontaneous Emission (SASE) mode; the soft x-rays are emitted at 250 Hz repetition rate.

Upgrade-1 increases the soft x-rays repetition rate to 1 kHz by virtue of additional klystron power supplying the accelerating structures, in order to keep the average RF power in the structures constant.

Upgrade-2 adds two features to Upgrade-1: i) soft x-rays can be produced in Echo-Enabled Harmonic Generation (EEHG) mode providing full longitudinal coherence, and hard x-rays in self-seeding mode for much-improved longitudinal coherence compared to SASE; ii) soft and hard x-ray pulses can be produced simultaneously and transmitted at the sampling rate of 100 Hz to the same end-station for FEL-pump FEL-probe experiments which implies both soft and hard x-rays can be transported to laser same stations as requested by users.

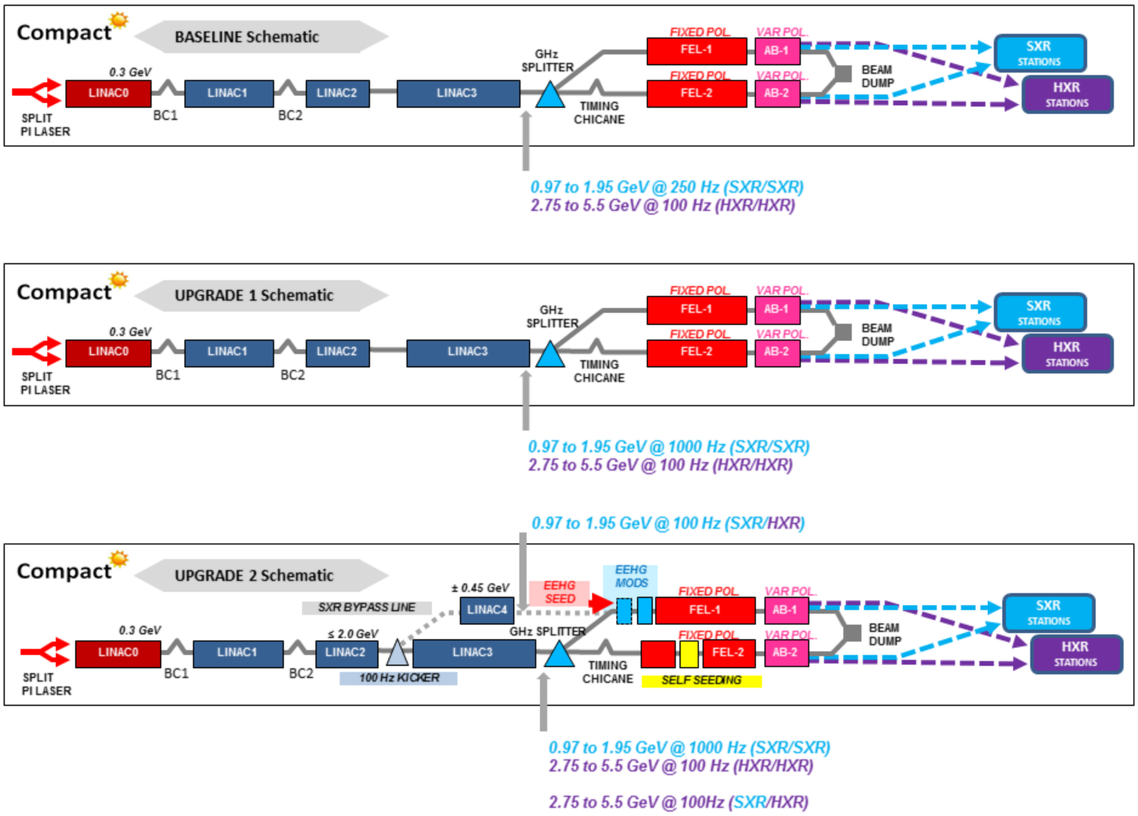


Figure 2: CompactLight layout. Twin electron bunches at several hundreds' of ps time separation can be produced at the photo-injector, and compressed twice in bunch compressors (BC1, BC2) for driving high gain soft and hard x-ray FELs. Linac0 includes C-band accelerating structures, while the remaining Linacs are X-band accelerating structures. The GHz splitter is a transverse S-band RF deflecting cavity. FEL-1 and FEL-2 are made of identical circularly polarized superconducting undulators, followed by in-vacuum cryogenic permanent magnet afterburner undulators for full control of polarization at the end-station.

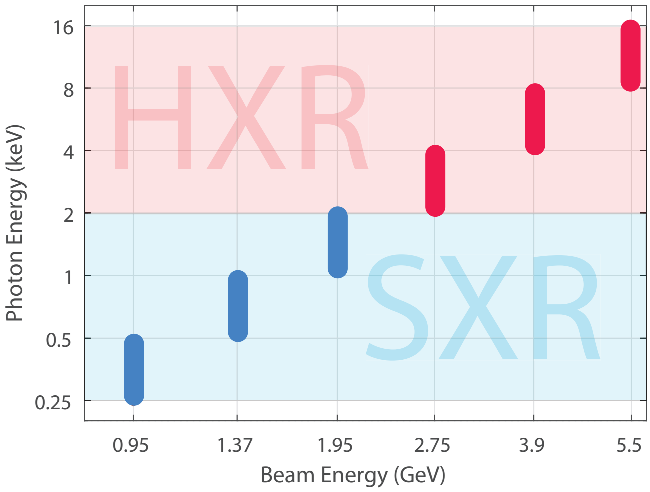


Figure 3: Photon energy versus electron beam energy.

1.3 Tables of Parameters

Table 1: Targeted features of CompactLight FEL. Peak brilliance is in unit of ph/s/mm^2/mrad^2/0.1% BW(*).

Parameter	Unit	Soft X-ray	Hard X-ray
Max. repetition rate	kHz	1	0.1
Photon energy	keV	$0.25-2.0$	$2.0-16.0$
Wavelength	nm	$5.0-0.6$	$0.6-0.08$
FEL tuning range at fixed energy		$\times 2$	$\times 2$
Peak brilliance @16 keV	(*)	10^{31}	10^{33}
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

Table 2: Operating modes of CompactLight FEL. B = baseline; U1 = Upgrade-1; U2 = Upgrade-2; HH = twin hard x-ray pulses; SS = twin soft x-ray pulses.

Operating Mode	FEL-1 λ-range	FEL-2 λ-range	L0-L1-L2-L3 Rep.Rate [Hz]	L3 Final E [GeV]	L4 Rep.Rate [Hz]	L4 Final E [GeV]
BASELINE						
B-HH	HXR	HXR	100	2.75-5.5		
B-SS	SXR	SXR	250	0.95-1.95		
UPGRADE-1						
U1-HH	HXR	HXR	100	2.75-5.5		
U1-SS	SXR	SXR	1000	0.95-1.95		
UPGRADE-2: U1 plus extra mode						
U2-SH	SXR	HXR	100	2.75-5.5	100	0.95-1.95

2 Injector

2.1 Layout

The linac low energy section is made of a normal conducting photo-cathode RF gun for the generation of high brightness electron bunches. Copper cathode is the baseline choice and especially suited for high repetition rate operation. $\mathrm{Cs_2Te}$ cathode is considered as an alternative option in order to minimize the impact of micro-bunching instability, due to longer relaxation time with respect to Cu, though at the expense of cathode lifetime, and therefore better suited for low repetition rates. Room for a laser heater (LH) is taken into account, which will be devoted to minimize the impact of micro-bunching instability on the FEL performance. A summary of the CompactLight injector beam parameters as the result from particle tracking runs, and in accordance to the target features of the facility, are listed in Table 3.

2.2 Radiofrequency

The baseline choice for the radiofrequency of the injector is dictated by several considerations:

- generation of a six-dimensional normalized electron beam brightness $B_n = I/(\varepsilon_{nx}\varepsilon_{ny}\sigma_\delta) \approx 10^{21}\mathrm{A/m^2}$, corresponding to peak current at several kA-level, normalized emittances smaller than 0.2 μm and relative energy spread smaller than 0.01% at the undulator entrance;
- production of high brightness beams at repetition rates in the range 0.1-1 kHz;
- compactness of the overall injector layout, including preparation (linearization) of the beam longitudinal phase space for magnetic compression at higher energies;
- technology risk assessment of the gun and of the high harmonic cavity (linearizer).

As a result, RF C-band is chosen for the gun and the first two accelerating structures in Linac0 [2], followed by X-band structrues. This choice minimizes the risk assessment both on the gun, especially at high repetition rate, and on the linearizer, whose peak voltage is minimized by a C-band frequency with respect to a higher frequency. The linearizer is a short Ka-band cavity, with maximum peak accelerating voltage of 17 MV. Table 4 lists the specifications of the C-band gun.

A full X-band linac, i.e., X-band gun and Linac0 is envisioned as an upgrade option for a more compact injector layout. In this case, preliminary beam dynamics studies indicate a Ka-band frequency for the linearizer with peak voltage in the 10 MV range and peak gradient at 10 MeV/m scale.

2.3 Beam Dynamics

Figure 4 illustrates the optimized C-band injector layout up to acceleration into the X-band structures. The gun is followed by few accelerating structures (Linac0), which bring the beam energy up to 250-300 MeV, where the first bunch compressor (BC1) is installed. Gun and Linac0 are externally coupled to solenoids for minimization of the beam transverse emittance during beam transport in space charge-dominated regime. In order to reach peak currents of few kA at the entrance of the undulator section, a total bunch length compression factor of ≈150 is required. This compression can be firstly conducted at the injector, by operating it in the so-called velocity bunching (VB) mode, which compresses the bunch length by a factor 3 and allows it to reach a peak current of 60 A at the entrance of BC1. A high harmonic cavity, named linearizer, is installed in the injector area for the linearization of the compression process, i.e., optimum control of the bunch current profile at higher peak currents.

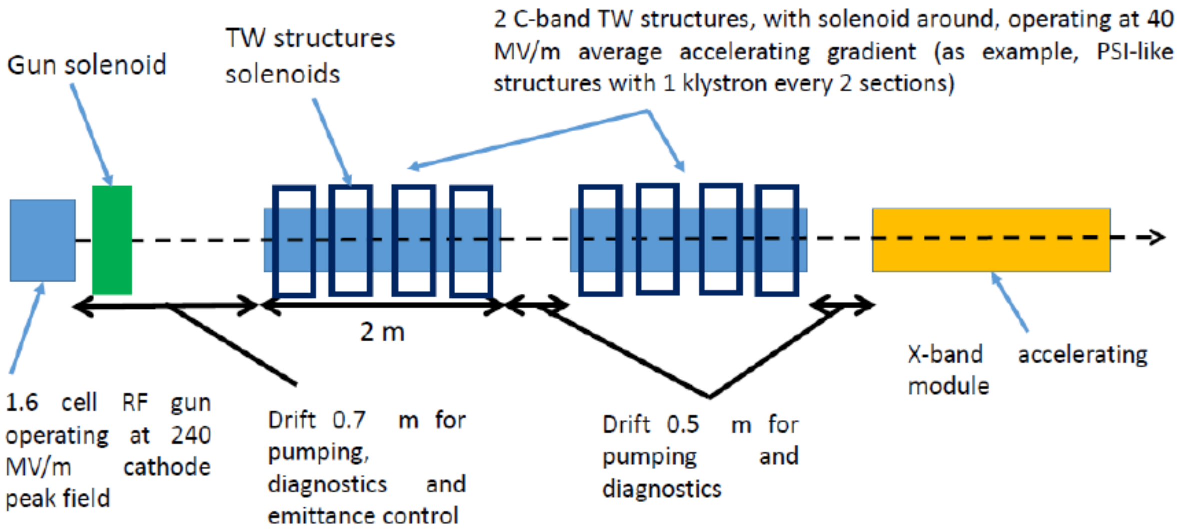


Figure 4: C-band injector: from gun to first X-band accelerating module.

2.4 Tables of Parameters

Table 3: Injector beam parameters.

Parameter	At gun exit	At L0 exit	Units
Repetition rate	0.1, 0.25, 1		kHz
Charge	75		pC
Proj. norm. emittance (RMS)	0.15 (x), 0.15 (y)		μm rad
Energy	6	280	MeV
Rel. energy spread (RMS)	0.7	0.5	%
Bunch duration (RMS)	1.2	0.4 (w/ VB)	ps
Peak current (core)	20	60 (w/ VB)	A

Table 4: C-band gun RF parameters at 100 Hz. Values in parenthesis refer to the TM_{020}-type input coupler.

Parameter	Value	Units
Repetition rate	100	Hz
Resonant frequency	5.712	GHz
$E_{cath}/\sqrt{P_{diss}}$	65 (55)	$MV/mMW^{0.5}$
RF input power	40 (70)	MeV
Peak field at cathode	160–240	MV/m
Quality factor	11000 (14000)	
Filling time	150	ns
Coupling coefficient	3	
RF pulse duration	180	ns
Pulse heating	<40	C
Average diss. power	200	W

3 Main Linac

3.1 Layout

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 150 for a final maximum peak current of 5 kA to generate hard x-rays at 100 Hz. A two-stage magnetic compression scheme is adopted in the main linac, in addition to the optional velocity bunching implemented in the injector. Table 5 lists the main electron beam and FEL parameters for the 100 Hz repetition rate scenario.

The main linac includes all identical X-band accelerating structures separated by single quadrupole magnets. The intra-linac sections typically include one quadrupole, one beam position monitor inserted into the magnet, and one combined corrector magnet for trajectory control. Trajectory control for suppression of the single bunch beam break up instability also profits of wakefield monitors installed at the edges of each accelerating structure. Screens for electron beam visualization are planned to be installed at intermediate locations devoted to beam diagnostics.

3.2 Bunch Length Compressors

The magnetic bunch compressors are symmetric 4-dipoles chicanes with beam diagnostics in the inner drift region. Small quadrupole magnets in the outer branches of the chicane are foreseen for tweaking of residual dispersion. The compressors are tuneable in angle in the range 0 – 4.5 deg. Bend-plane emittance growth due to emission of coherent synchrotron radiation (CSR) is minimized by means of small horizontal betatron functions in the second half of the chicanes. The local compression factors are ≈9 at BC1 and ≈5 at BC2, for a maximum total compression factor of 100 when operating the injector in velocity bunching mode.

The first magnetic bunch compressor (BC1) is planned to be used in the beam energy range 250 – 300 MeV. X-band linacs Linac1, Linac2 and Linac3 downstream the injector section Linac0, separated with a second bunch compressor (BC2), will boost the beam energy up to approximately 5.5 GeV at 100 Hz. The beam energy at the BCs, at the intermediate extraction point for the soft X-ray (SXR) FEL and at the linac end for the hard X-ray (HXR) FEL, is mainly constrained by the requirement of SXR FEL operating at 1 kHz. The peak X-band accelerating gradient at 100 Hz is 65 MV/m, and approximately 30 MV/m at 250 Hz and 1 kHz.

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 longitudinal 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 SXR and HXR FEL extraction point, and a final relative energy spread smaller than 0.1% (projected value). Linac phasing far from the accelerating crest is kept smaller than 30° X-band in order to limit beam energy jitter due to RF phase jitter. Table 6 lists the main electron beam and linac parameters relevant to magnetic compression, for the extreme scenario of 5 kA final peak current at 5.5 GeV out of Linac3.

3.3 Accelerating Structures

For the main linac, our goal is to define a standardised RF unit based on the CLIC technology, 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. This choice will greatly simplify the industrialisation process, with a considerable reduction in production costs. RF parameters of the standardized CompactLight X-band accelerating structure are reported in Tab. 7.

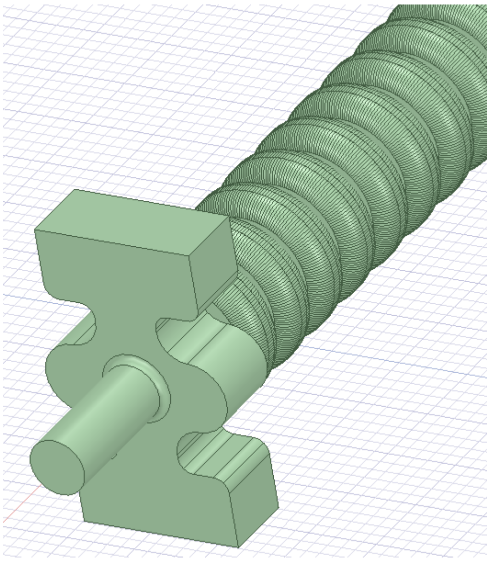


Figure 5: 3-D rendering (zoom) of the X-band accelerating structure with input coupler.

3.4 RF Distribution System

The RF distribution system has been optimized with the aim of ensuring FEL repetition rates (RRs) of 0.1, 0.25 and 1 kHz while minimizing number of RF plants and therefore overall cost from RF power sources and waveguides. Also, SXR and HXR FELs should be able to run simultaneously.

The baseline configuration of the layout will be run in the so-called *dual mode*, i.e., a single RF source supplies the linac in two operating modes, i.e., 0.1 kHz and 0.25 kHz. This is the cheapest solution but limited in RR. The two RRs are associated to the peak accelerating gradient of 65 MV/m and 32 MV/m respectively, which implies a scaling of the magnet strengths for ensuring the same optical functions along the linac. An X-band SLED is adopted at 0.1 kHz, and it is by-passed at 0.25 kHz; still, the klystron always operates at its nominal working point.

Upgrade-1 and Upgrade-2 will operate in the so-called *dual source*, i.e., an additional klystron is connected to the RF module and so two RF sources supply the linac for the RR of 0.1 kHz and 1 kHz. In this case, SXR and HXR FELs will operate simultaneously at 0.1 kHz only. The peak accelerating gradient at 1 kHz is 30.4 MV/m, and the linac maximum energy is approximately halved with respect to the 0.1 kHz case. The dual source solutions is largely inspired by the commercially available Canon and CPI RF sources, e.g., running up to 400 Hz. Both Canon and CPI companies have R&D programs towards the realization of klystrons with 10 MW peak power, 1.5 μs pulse duration, operational up to 1 kHz repetition rate.

The dual source RF distribution is sketched in Fig. 6. The main klystron RF parameters for all the three RRs are in Tab. 8. The RF distribution depicted in Fig. 6 connects 2 klystrons to 4 accelerating structures; these form one accelerating module of 3.6 m active length. As said before, by switching or combining two RF sources, a high gradient at high repetition rate is guaranteed. If a combination of sources were implemented as a third upgrade scenario, accelerating gradients higher than 30 MV/m would become available at RRs in the intermediate range 0.1-0.25 kHz.

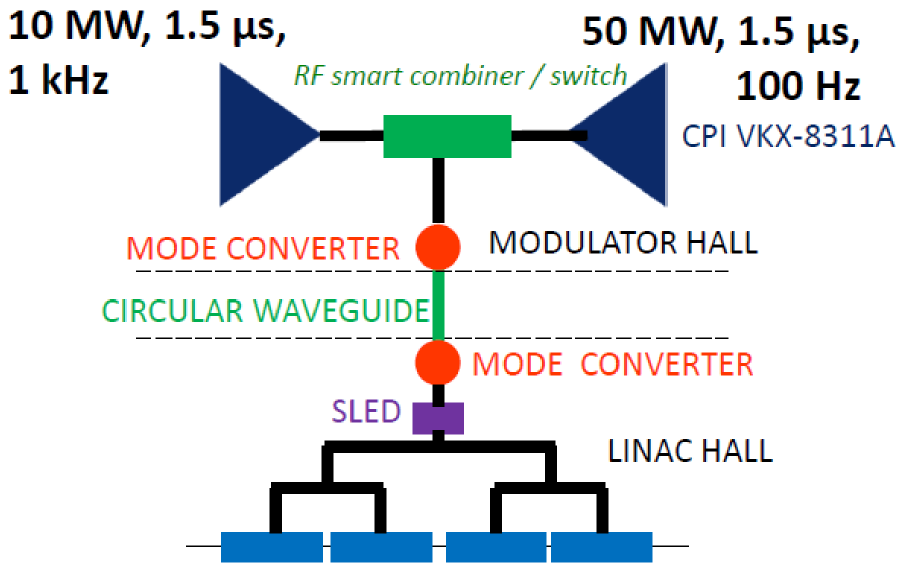


Figure 6: RF distribution system for the main linac supplying electron beam repetition rates of 0.1, 0.25 and 1 kHz.

3.5 Magnetic Lattice

The magnetic lattice of the main linac is based on a FODO cell interleaved by low-β_x insertions in correspondence of the magnetic compressors, as shown in Fig. 7. The average betatron functions are approximately 6 m in Linac1 and 8 m along Linac2 and Linac3. Such reduced values ensure proper control of the transverse wakefield instability, which is consistent with BBA-trajectory correction techniques applied upon transverse misalignment of quadrupole magnets and accelerating structures with rms deviations of the order of < 50 μm and < 100 μm respectively, quadrupole roll error < 50 μrad and structures roll error < 100 μrad. The standard quadrupole magnet has magnetic and physical length of 0.06 m and 0.08 m repectively. The maximum field gradient is 47 T/m, for a maximum integrated field of 2.82 T. The pole tip field is 0.47 T for a bore radius of 10 mm; the vacuum chamber is assumed to be round with internal diameter of 15 mm. The maximum quadrupole normalized strength is 2.6 (26) m^{-2} at 5.5 (0.55) GeV. The magnetic design of the quadrupole magnet is illustrated in Fig. 8. Coils for combined horizontal and vertical trajectory steering are included in the design.

The linac fill factor is $> 70\%$ in all sections. Figures 9, 10, and 11 illustrate the distribution of drift sections in between accelerating structures for Linac1, and the higher energy linac sections, respectively, assuming the dual source RF distribution depicted above [3]. The total linac length from cathode to exit of Linac3 (HXR beam line) is less than 190 m, and includes 104 X-band accelerating structures in total [4].

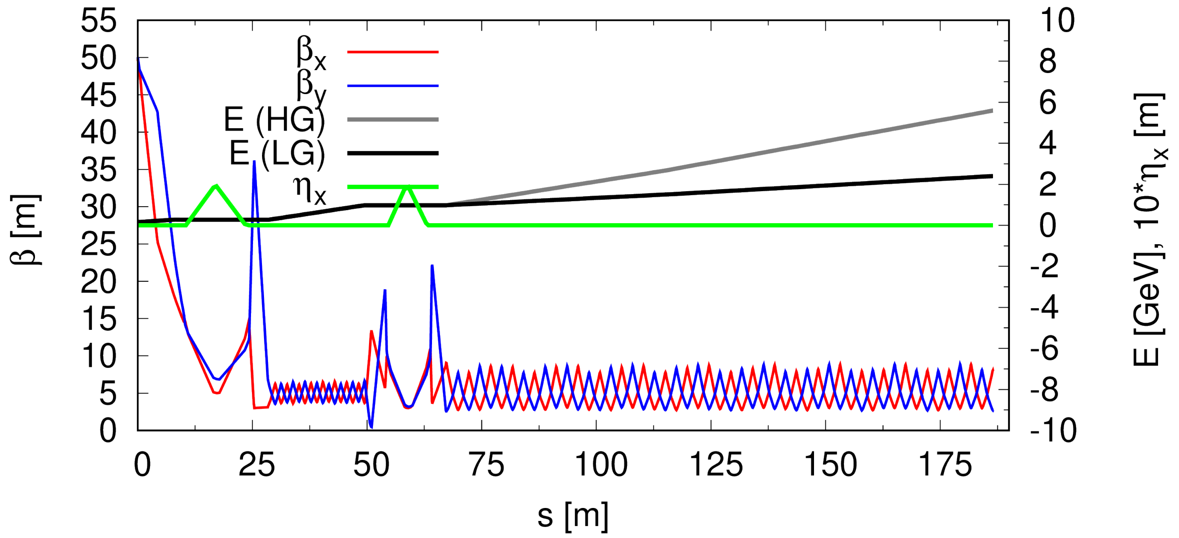


Figure 7: Optics functions from end of the S-band injector to Linac3 end. The two dispersion bumps are in correspondence of BC1 and BC2.

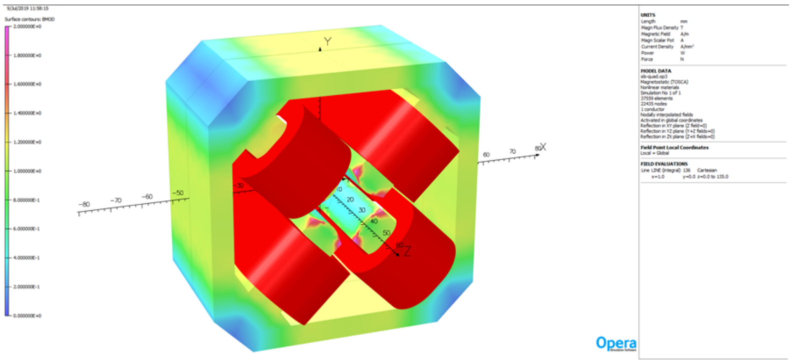


Figure 8: Magnetic design of the standard quadrupole magnet. Coils for combined horizontal and vertical trajectory steering are included but not shown.

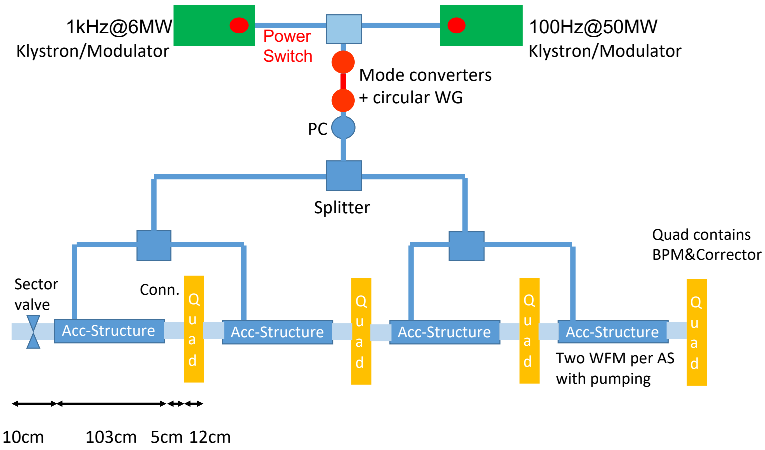


Figure 9: Linac0 module layout. Filling factor: 71%.

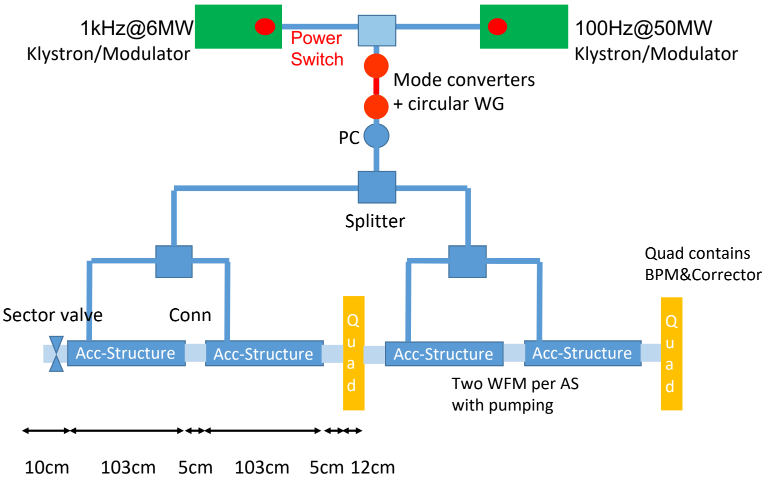


Figure 10: Linac1, Linac2, and Linac4 module layout. Filling factor: 76%.

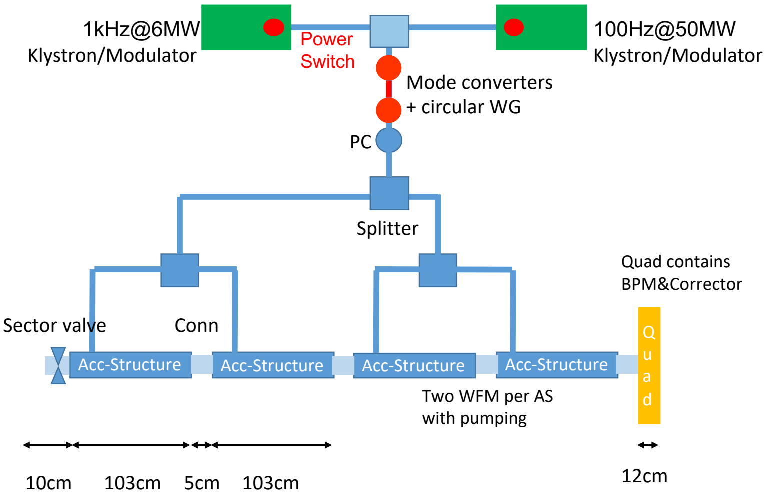


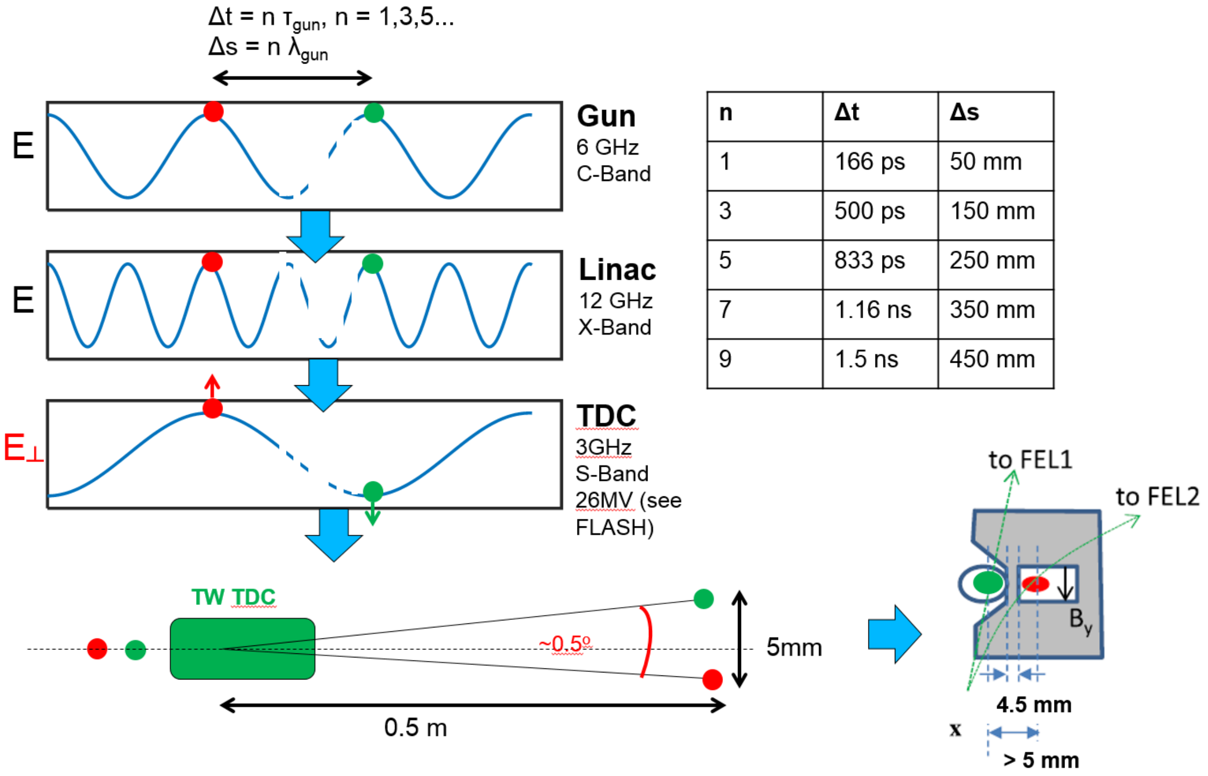
Figure 11: Linac3 module layout. Filling factor: 78%.

3.6 Beam Distribution System

The CompactLight FEL design foresees, already in its baseline configuration, the simultaneous and independent operation of two FEL lines, namely, FEL-1 and FEL-2, as shown in Fig. 2. Such a configuration provides either the Simultaneous Operation (SO) of two end stations, or the implementation of FEL Pump-FEL Probe (PP) experiments at one end station. This last option only envisages SXR/SXR and HXR/HXR pump-probe in the baseline and upgrade-1 configuration. SXR/HXR pump-probe is in addition enabled by the upgrade-2, also by virtue of photon beam transport lines, from the undulator end to the experimental chamber, designed for the transmission and focusing of both SXR and HXR photon pulses. The SO and the PP schemes are made feasible by exploiting the generation and acceleration of twin bunches in the linac. In the following, we will consider the baseline option of a C-band injector followed by standard X-band accelerating structures.

The photo-injector laser is split into two pulses separated by 3 RF cycles of the C-band gun or 500 ps; the two pulses generate identical electron bunches having the same RF phase relative to the accelerating electric field. This time separation corresponds to 6 RF cycles in the X-band linac. A separation larger than approximately 200 ps is recommended in order to keep beam break up instability of the trailing bunch well under control, with a projected emittance growth at the linac end below 10%. This estimation is consistent with random rms misalignment of X-band modules and quadrupoles by 100 μm and 50 μm respectively, in the presence of trajectory correction and dispersion-free steering.

The twin bunches will follow identical dynamics in the accelerator. In the baseline and upgrade-1 configuration, they will be separated in the horizontal plane by means of a sub-harmonic, i.e., S-band transverse deflecting cavity. By virtue of the odd number of C-band cycles in the injector, the twin bunches will be horizontally deflected by kicks with opposite sign at the deflector. About 30 MV peak deflecting voltage at the maximum beam energy of 5.5 GeV will impose angular kicks of the order of half a degree, and will allow the two bunches to be separated by $\approx$5 mm after a 0.5 m-long drift section. At such position, a DC out-of-vacuum thin septum magnet will direct the leading bunch to FEL-1, and the trailing bunch to FEL-2. A schematic of this beam manipulation is shown in Fig.12.



n	Δt	Δs
1	166 ps	50 mm
3	500 ps	150 mm
5	833 ps	250 mm
7	1.16 ns	350 mm
9	1.5 ns	450 mm

Figure 12: Schematic of the twin bunches splitting by an RF horizontal deflecting cavity, sub-harmonic of the C-band injector. The deflector is followed by a DC thin septum magnet.

An alternative splitting system foresees an accelerating S-band linac module at the end of Linac3, with peak voltage of 55 MeV, to induce a mean energy separation of the twin bunches at 1% level (one bunch sitting at the S-band on-crest phase, the other one sitting at the decelerating crest). The S-band module is followed by a 0.5 m-long, 1 T-magnetic field DC horizontal bending magnet, which deflects a 5.5 GeV beam by 5 deg. After ≈ 18 m from the dipole, the two bunches, whose angular separation is 0.05 deg, are separated by 5 mm, where the aforementioned septum is located for final splitting towards FEL-1 and FEL-2. The S-band accelerator option relaxes the tolerances on the RF phase jitter w.r.t. the transverse deflecting cavity, but it adds in total about 20 m of longitudinal occupancy to the layout.

Either the S-band deflector or the S-band linac section depicted so far satisfies the SO scheme. The PP scheme, instead, requires further synchronization efforts of the twin bunches at the undulator. Since PP experiments typically require a continuous scan of the relative delay of the pump and the probe pulse by at least few ps around synchronization, the leading bunch directed to FEL-1 has to be delayed by 500 ps w.r.t. the trailing bunch. This is accomplished by means of a dog-leg-like switchyard from the septum to FEL-1. This has to satisfy a minimum longitudinal occupancy of 10 m, leading to a lateral separation of the undulator lines by ≈ 1.5 m. However, in order to minimize the bending angles (< 5 deg per dipole magnet) in the switchyard for minimum impact of CSR on the beam emittance, parasitic energy dispersion and energy distribution, a rectilinear length not smaller than 20 m is recommended at the minimum beam energy of 0.95 GeV. The FEL lines will then be laterally separated by ≈2.5 m.

On top of this, fine tuning of the pump-probe relative delay will be allowed by a small 4-

dipole chicane in front of the FEL-2 line (±5 ps or $R_{56} = -6$ mm,< 10 m total length), and by a split-and-delay line (±30 ps) on the photon beam path towards the end-station.

As mentioned earlier, the upgrade-2 configuration is the only one allowing the simultaneous generation of SXR and HXR FEL pulses, at 100 Hz. In this case, the aforementioned splitting system, followed by a dog-leg-like switchyard line, has to be replicated at the end of Linac2, so bringing the leading bunch to FEL-1 for SXR emission. The trailing bunch only will be reaching the end of Linac3 for HXR production.

It is worth mentioning that any longer time separation of the twin bunches at the injector, say bigger than few ns, would be compatible both with the long range transverse wakefield instability, and with the adoption of a fast stripline kicker of ns-scale rise and fall time for beam splitting at high energy. However, such large time separation would require much longer switchyards at high energy, and therefore reducing the compactnesses of the overall layout.

3.7 Tables of Parameters

Table 5: Electron beam parameters at undulator entrance.

Parameter	**Value**
Max. Energy	5.5 GeV @ 100 Hz
Max. Peak Current	5 kA
Norm. Slice Emittance	0.15 μm rad
Bunch charge	< 100 pC
Bunch duration (RMS)	< 50 fs
Slice Rel. Energy Spread	0.01%
Max. repetition rate	1 kHz

Table 6: Magnetic compressors parameters.

Parameter	**Unit**	**BC1**	**BC2**
Beam energy	GeV	0.25-0.3	1.4-1.6
Compression factor		10-15	5-10
Max. peak current at exit	kA	0.7	5
Min. bunch duration at exit (RMS)	fs	25	2
Max. $\lvert R_{56} \rvert$	mm	32	9
Max. rel. energy spread (RMS)	%	2	1.5
Geometry		chicane	chicane
Dipole bending angle	mrad	52.8	36.7
Dipole magnetic arclength	m	0.4	0.4
Total length	m	13.1	8.5
Tweaking quadrupoles		yes	yes

Table 7: X-band accelerating structure RF parameters.

Parameter	Unit	Value
Frequency	GHz	11.9942
Phase advance	rad	$2\pi/3$
Average acc. gradient	MV/m	65 @ 0.1 kHz 32 @ 0.25 kHz 30.4 @ 1 kHz
Average iris radius $\langle a \rangle$	mm	3.5
Cell Iris radius range	mm	4.3-2.7
Cell length	mm	8.332
Total length	m	0.9
Shunt impedance (effective)	$M\Omega/m$	90-131 (387)
Group velocity	%	4.7-1.0
Power$_{out}$/Power$_{in}$		0.215
RF pulse duration	μs	1.5
Group velocity	%	4.5-1.0
Filling time	ns	144
Input power per structure	MW	9.8
Unloaded (ext.) SLED Q-factor	10^3	180 (23)
Structures per module		4

Table 8: X-band klystrons RF parameters.

Parameter	Unit	0.1 kHz	0.25 kHz	1 kHz
Frequency	GHz	11.9942		
Max. RF peak power	MW	50	50	10
RF pulse length	μs	1.5	0.15	1.5
SLED		on	off	on
Ave. diss. power per structure	kW	1	0.3	2.2
Peak input power per structure	MW	68	10.6	14.8
Ave. input power per structure	MW	44	10.6	9.6
Max. energy gain per module	MeV	234	115	109

Table 9: Operating scenarios of the RF distribution system: dual mode (Baseline) and dual source (Upgrade-1, Upgrade-2).

Parameter	Unit	Dual mode		Dual source	
Operating Mode		**B**		**U1, U2**	
Repetition rate	kHz	0.1	0.25	0.1	1
Linac active length	m	94			
Number of structures		104			
Number of modules		26			
Number of klystrons		26		26 + 26	
Peak acc. gradient	MV/m	65	32	65	30.4
Energy gain per module	MeV	234	115	234	109
Max. energy gain	MeV	6084	2990	6084	2834

4 Undulator

4.1 Requirements

A comparison of available undulator technological solutions and some perspective studies for the near future allowed a filtering process of the main electron beam and undulator parameters required to meet the CompactLight user wish list [5]. In this process of review and selection of undulator parameters and technology, the following requirements/constraints have been taken into account:

- photon wavelength range vs. electron beam energy (resonance condition);
- tuning across photon energies will primarily be achieved by undulator scanning rather then electron energy scanning, in order to maximize efficient operation of the facility. Given that both SXR and HXR regimes require a factor of 8 photon energy scaling to be covered with a few discrete electron beam energies, the undulator should provide a factor of 2 wavelength tuning;
- variable, selectable polarization in both SXR and HXR range;
- two-colour operation achieved by double bunches sent to separate undulators. The required wavelength tuning of 10-20% is satisfied by the 2-fold wavelength tuning specified above;
- the ratio of FEL peak brilliance and saturation length should be maximized, as it is an index of performance vs. compactness;
- the FEL peak brilliance should be maximized by itself because there is a specific user requirement for a minimum brilliance;
- the aforementioned figures of merit should be maximized for a maximum electron beam energy lower than any other present x-ray FEL facility, and in particular lower than at SwissFEL for a higher maximum photon energy.

4.2 Technology

The brilliance and the brilliance-to-saturation length ratio are plotted for different undulator technologies in Fig. 13. Electron beam parameters for HXR emission at 16 keV are assumed, as this is the most demanding scenario for the electron beam and therefore the FEL performance: peak current $I = 5$ kA, normalised transverse emittance $\varepsilon_n = 0.2$ mm-mrad, relative RMS energy spread $\sigma_\gamma/\gamma_0 = 10^{-4}$ and average β-function $\bar{\beta} = 9$ m. In each plot the horizontal axis is the undulator period λ_u and the vertical axis is the undulator K_{rms}. Each line shows the dependence of K_{rms} vs λ_u for a different undulator technology, as represented in the legend. For some technologies a full parameterisation over the space is not available—these technologies (for example the Microwave undulators) are represented by single points on the plot. The coloured region represents the $[K_{rms}, \lambda_u]$ parameter space in which the undulator resonant wavelength lies between $\lambda_r = 0.155$ nm (top edge) and $\lambda_r = 0.0775$ nm (bottom edge). The colour represents the value of the figure of merit, either B or B/L_{sat}.

The interpretation of these plots is as follows. The intersection of each undulator curve with the $\lambda_r = 0.155$ nm line defines the period required for that undulator, at that beam energy, to be resonant at $\lambda_r = 0.155$ nm. To tune to $\lambda_r = 0.0775$ nm the undulator K strength is then reduced. Only those technologies for which the $[K_{rms}, \lambda_u]$ curve intersects the $\lambda_r = 0.155$ nm line at $\lambda_u < 12$ mm provide any output at $\lambda_r = 0.0775$ nm. Though not shown, it becomes clear that the higher the electron beam energy, the more relaxed the requirements on the undulator parameters become, for the same wavelength range. But, the merit functions are low for those technologies with weaker field, indicating that a threshold could be defined in principle.

It is noted that these calculations are obtained for an ideal case, in reality the performance may be slightly degraded by other effects, such as; the bunch may have an energy chirp; or there may be bandwidth broadening or power reduction due to undulator wakefields. Therefore, a factor of two of contingency is added to the required peak brilliance, i.e. the selected choice of undulator technology should provide a $B > 2 \times 10^{33}$ ph/s/mm^2/mrad$^2/0.1\%$ BW at all photon energies. We observe that:

* the merit functions are always stronger for those undulator technologies which provide the highest field;

* SCU shows superior performance w.r.t. CPMU and IVU for the SXR FEL wavelength range of interest and beam energies in the range 2-4 GeV;

* a 4 GeV beam gives only 20% higher peak brilliance than a 2 GeV beam, while a 2 GeV beam gives 30 % better ratio of peak brilliance to saturation length than a 4 GeV beam;

* given the simultaneous requirement of large wavelength tuning (factor 2 in photon energy in both the SXR and the HXR regime) and two-colour operation with nearby photon energies, both undulator lines are forced to have identical parameters and tuneability.

4.3 Radiator

The semi-analytical predictions in the figures above were supported by time-dependent FEL simulations, whose results are summarized in Tab. 10. The present status of FEL studies confirm that the SCU linearly - and possibly circularly - polarized undulator technology is the most efficient technology for lasing in the specified wavelength ranges. CompactLight FEL will therefore adopt two identical SCU lines supplied by different electron beam energies. Within the individual SXR and HXR photon energy range, six discrete electron beam energies are identified; at each beam energy, the undulator field is regulated in order to allow a 2-fold tuning of the photon energy, as listed in Tab. 11. Doing so, a peak brightness at the highest photon energy of 16 keV, at 10^{33} level in standard units, and a fwhm spectral bandwidth at 0.1% level is expected. The saturation length is approximately 20 m, with peak power approaching 10 GW at the HXR high energy edge.

The variable selectable polarization is provided with a few-segment-long afterburner in-vacuum cryogenic permanent magnet APPLE-X type undulator. The SCU + afterburner option assumes the radiation from the SCU is blocked before the afterburner. In consequence, the degree of polarisation is close to 100 %. The way to achieve this in practice involves aligning the afterburner at a small angle to the SCU (beam diverted scheme) or installing an inverse taper on the SCU to suppress the background power coming from the main undulator, but still allowing the electron beam to bunch. Experimental results obtained by the inverse taper scheme and reported in the literature, demonstrate successful polarisation control successfully between a planar undulator and a helical afterburner.

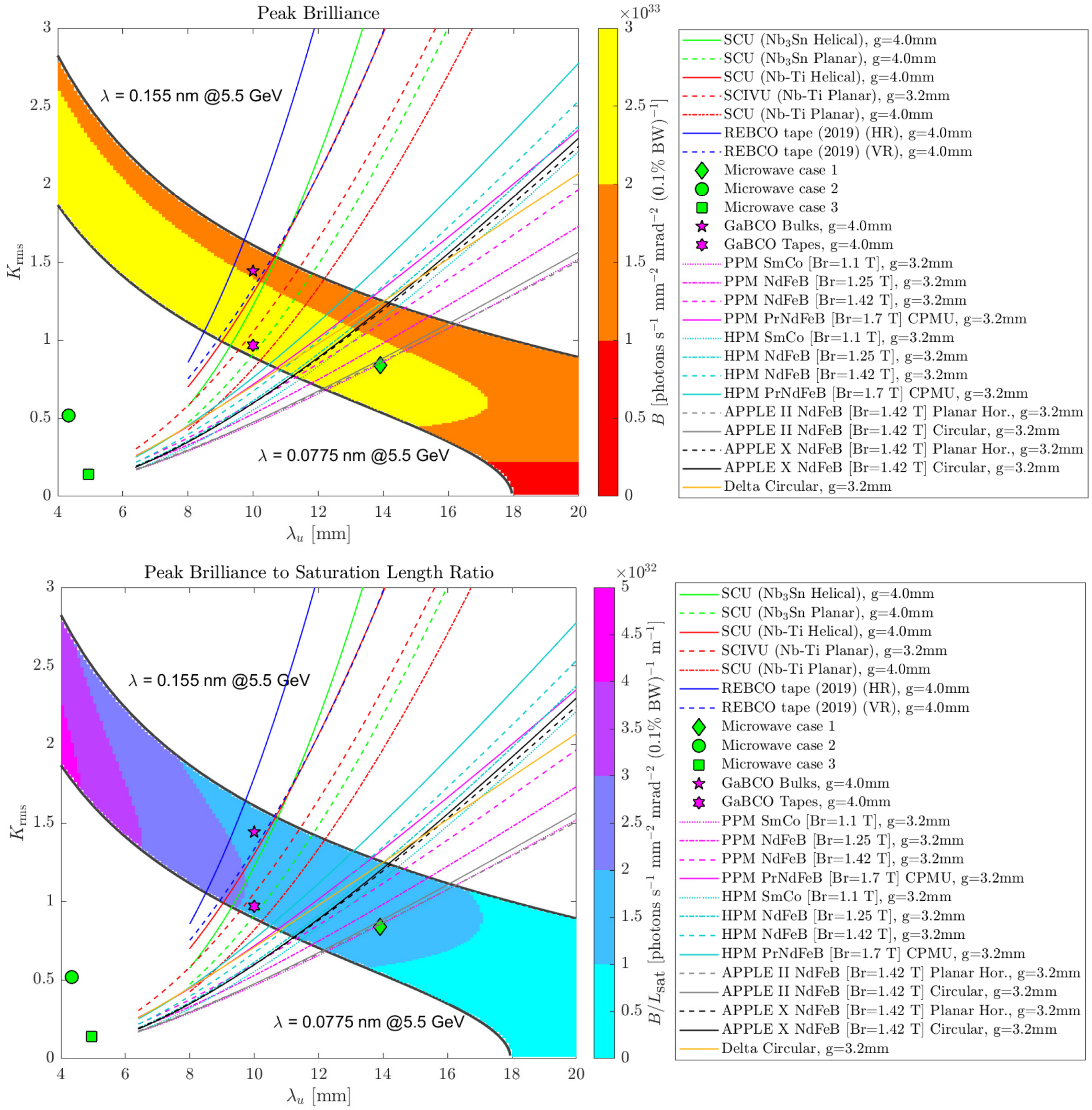


Figure 13: Peak brilliance (top) and peak brilliance to saturation length ratio (bottom), for a 5.5 GeV electron beam energy, as a function of undulator period, for different undulator technology as predicted by semi-analytical model.

The undulator-radiator design follows the approach of a minimally segmented FEL array. The complete beam line for the CompactLight base line facility design would consist of 16 interconnected cryostats, each housing 1 undulator magnet, 1 phase shifter including horizontal and vertical correctors, and 1 quadrupole magnet with integrated beam position monitor. All magnets and diagnostic components will be operated at 4.2 K, which will also be the temperature of the complete beam pipe. Cooling will be done by means of liquid Helium (forced flow), supplied by a central cryoplant. A cooling power of 1 W/m floor length at 4.2K would likely be required, i.e. 40 – 60 W depending upon technical solutions for the transition modules at both ends of the cryostat array, transfer lines and liquid He distribution system. The main parameters of the SCU and IVU are listed in Tab. 12.

4.4 Tables of Parameters

Table 10: 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 [$\times 10^{33}$ ph/s/mm^2/mrad^2/0.1% BW]	2.39	2.37	1.98	2.18

Table 11: Photon energy ranges and electron beam parameters.

Parameter	**Unit**	**SXR**			**HXR**		
Repetition rate	kHz	0.1, 0.25, 1			0.1		
Photon energy range	keV	0.25-0.5	0.5-1	1-2	2-4	4-8	8-16
Electron beam energy	GeV	0.97	1.37	1.95	2.75	3.9	5.5
Minimum peak current	kA	0.35	0.65	0.93	1.5	2.5	5
Slice energy spread (RMS)	%	0.05	0.04	0.03	0.02	0.015	0.01
Normalised slice emittance (RMS)	μm rad	0.2					
Bunch charge	pC	75					

Table 12: FEL-1 and FEL-2 undulator parameters.

Parameter	**Unit**	**Main radiator**	**Afterburner**
Technology		SCU	IV-CPMU
Period length	mm	13	17
Minimum full gap	mm	4	3
Undulator parameter a_w		0.62–1.32	0.3–1.5
Maximum field on-axis	T	1.1	1.2
Segment length	m	1.8	1.8
Module length	m	2.3	2.0
Total length	m	37	6
Polarization		circular	variable

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