

THE X-BAND FEL COLLABORATION

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Abstract

The X-band FEL collaboration is currently designing an X-ray free-electron laser based on X-band acceleration technology. Due to the higher accelerating gradients achievable with X-band technology, a X-band normal conducting linac can be shorter and therefore potentially cost efficient than what is achievable with lower frequency structures. This cost reduction of future FEL facilities addresses the growing demand of the user community for coherent X-rays. The X-band FEL collaboration consists of 12 institutes and universities that jointly work on the preparation of design reports for the specific FEL projects. In this paper, we report on the on-going activities, the basic parameter choice, and the integrated simulation results. We also outline the interest of the X-band FEL collaboration to use the electron linac CALIFES at CERN to test FEL concepts and technologies relevant for the X-band FEL collaboration.

INTRODUCTION

A major factor in the cost of the construction of a linac driven FEL facility is the accelerator technology adopted. For normal conducting facilities, a substantial part of the costs is determined by the linac operating frequency, which strongly influences space requirements and power consumption. Most of the operational facilities use S-band linacs, operating at 3 GHz, or newly designed C-band linacs, operating at 6 GHz. The use of higher frequencies can allow an increase of the operating gradient and the efficiency, with an overall reduction of the machine length and the cost. These advantages could be further enhanced if the operating frequency can be extended to the X-band region (i.e. 12 GHz), where the operating gradients can be almost doubled compared to those of C-band structures. During the last decades, research and development of X-band accelerator technolo-

gies has seen a tremendous progress within the context of the next generation of electron-positron Linear Colliders, where very high gradients are necessary to achieve the multi-TeV beam energies within reasonable length. The possibility to operate X-band accelerating structures at gradients higher than 100 MV/m, has been recently demonstrated in the context of the CERN CLIC (Compact Linear Collider) Collaboration, with a very low RF Breakdown Rate (BDR/m < 3×10^{-7}) [1]. This has suggested that the X-band technology may represent a useful solution to get very compact and cost effective multi-GeV linacs, opening the way for new less expensive FEL facilities. This option seems to be even more attractive if we consider that most of the future X-ray FELs will be designed to operate with very short and low-charge electron bunches, minimising unwanted wake field effects. Starting from the FEL output specifications provided by users (i.e. wavelength range, energy per pulse, pulse duration, pulse structure, etc.), the objective of the X-band FEL collaboration is to analyse three possible scenarios: a soft X-ray FEL, a hard X-ray FEL and the extension of an existing facility. Other efforts involve identifying, designing and testing, a common X-band RF unit for the three sources, on a dedicated test stand. This effort will demonstrate the maturity of the technology, validating the hardware and the use of X-band in this area of strategic scientific interest.

COLLABORATION AND SPECIFIC INTERESTS

The X-band FEL collaboration consists of 12 institutes and universities (see affiliation of authors), which share the common interest of using X-band technology for FELs. Some of the envisioned projects within this collaboration are summarised in the following.

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Light Source Australia

The Australian Synchrotron (ASLS) is a third generation storage ring based light source in Melbourne. Presently, upgrade plans are being made to improve the X-ray beams available to the large user community. In the proposed upgrade concept, called AXXS (Australian X-band X-ray Source) [2], it is foreseen to exchange the existing DBA lattice of the storage ring with an MBA lattice. Since the current injector complex is not capable of producing beams with small enough emittances to allow an efficient injection into the MBA lattice, a new, low-emittance injector linac is being designed. It is based on X-band technology and accelerates the beams to the necessary energy of 3 GeV. Since the X-band linac can operate at a high repetition rate, it can be used simultaneously as an injector for a soft X-ray FEL. Also hard X-rays can be produced if the beam energy is increase by a second X-band linac from 3 GeV to 6 GeV. Due to the high acceleration gradients of the X-band technology, the restricted site length of 550 m is sufficient to accommodate such an hard XFEL.

Daresbury Laboratory

The CLARA FEL Test Facility project is under development at STFC Daresbury Laboratory, with the first accelerating section being installed later this year [3]. CLARA will be capable of testing new FEL schemes that have the capability to enhance the performance of short wavelength FELs worldwide. The primary focus of CLARA will be on ultrashort pulse generation, stability, and synchronisation. Enhancements in these three areas will have a significant impact on the experimental capabilities of FELs in the future. In addition to these stated aims CLARA will also be an ideal test bed for the demonstration of new accelerator technologies related to FELs. Initially CLARA is designed to be based on S-band linac sections to achieve the required energy of 250 MeV. However, a study has shown that the replacement of the last 4 m linac section by an X-band linac designed for FEL applications does not have any adverse impact on the bunch quality and would have the advantage of increasing the maximum beam energy to approximately 430 MeV, assuming a gradient of 65 MV/m [4].

FERMI@Elettra

FERMI [5, 6] is a fourth generation light source at the Elettra – Sincrotrone Trieste (Italy) Laboratory that functions as a user facility producing photons in the ultraviolet and soft X-ray wavelength regions (100–4 nm), with an S-band linac (3 GHz) presently operated up to 1.5 GeV. Its capabilities and photon range could be improved and extended to hard X-rays ($\lambda < 0.5$ nm) by increasing the linac energy up to 3.0–3.5 GeV. Using infrastructures and spaces already available, this upgrade can be reached adding a new X-band (12 GHz) linac segment working with a gradient of 65–70 MV/m, downstream the second bunch compressor of the present machine, as sketched in Fig. 1. This solution will also give the possibility to operate two independent sources

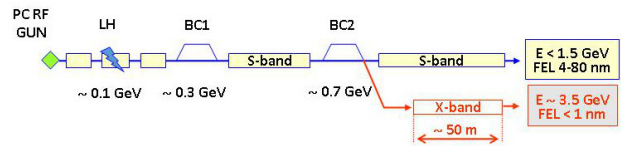


Figure 1: Schematic view of the Elettra facility with the planned upgrade in red.

at different wavelengths, which could be simultaneously used for experiments [7].

Shanghai Photon Science Center

Since 2009 the ring-based third generation light source SSRF (Shanghai Synchrotron Radiation Facility) supplies a large number of users with synchrotron radiation in the X-ray regime. To even further extend the capabilities of the Shanghai Photon Science Center, the Shanghai Soft X-ray FEL (SXFEL) was officially approved in 2011. In the first phase, the electron beam will be accelerated to an energy of 0.84 GeV with a combination of S-band and C-band acceleration structures. In the second phase, the beam energy will be increased to 1.3 GeV by replacing the C-band with X-band structures. For that reason, SINAP launched a significant R&D activity on the X-band technology [8], which includes a dedicated workshop. SINAP is also working on a proposal for a compact hard X-ray FEL (HXFEL), which will employ, apart from the S-band injector, exclusively X-band structures with an acceleration gradient of 65 MV/m to reach a beam energy of 6.4 GeV. In the studied upgrade scenario, the beam energy is increased to 8 GeV by raising the gradient to 80 MV/m.

Turkish Accelerator Center

The currently proposed program of the Turkish Accelerator Center (TAC) [9] has three relevant light source projects – Construction of TARLA (Turkish Accelerator and Radiation Laboratory in Ankara), and preparation of conceptual design reports of the Synchrotron Radiation Facility and the X-Ray Free Electron Laser facility. TARLA is a free electron laser operating in the infrared regime using superconducting RF acceleration, whereas the X-ray FEL will produce wavelengths of 0.1–10 nm or 5–10 nm. These facilities will cover a wide range of scientific interests in physics, chemistry, biology, life sciences, medicine, nanotechnology and engineering.

The TAC team has been working on a conceptual design report of these projects since 2010 with support of the Ministry of Development of Turkey. The team has been studying different accelerating structure such as the TESLA structure which is also related to the technology being employed in TARLA. Considering the cost of an XFEL facility, TAC wants to take advantage of the novel X-band cavities operating at room temperature which would reduce the overall price. The TAC team considers two different types of single pass FELs: (i) high repetition rate soft X-rays, (ii) low repeti-

Table 1: Design Parameter Summary of the Hard X-ray FEL

Parameter	Symbol	Value
Energy after injector	E_{inj}	0.3 GeV
Bunch length after injector	$\sigma_{z,inj}$	44 μm
Injector frequency	f_{inj}	3 or 12 GHz
Injector gradient	G_{inj}	20 or 65 MV/m
Energy after linac	E	6.0 GeV
Bunch length after linac	σ_z	<8 μm
Normalised emittance	$\epsilon_{x,y}$	0.3 μm
Bunch charge	n	250 pC
Linac frequency	f	12 GHz
Linac gradient	G	65 MV/m
Repetition rate	f_{rep}	100 Hz
Structure length	L_{str}	0.75 m
Undulator period	λ_U	15 mm
Undulator parameter (max)	K_0	1.4
X-ray wave length (min)	λ_γ	1 \AA
X-ray power (SASE at 1 \AA)	P_γ	9 GW

tion rate hard X-rays. To design both facilities they consider an S-band based injector, which would operate at low repetition rate, and an X-band based injector, which would allow the entire accelerator to operate at high repetition rate.

PROGRESS IN DETAILED DESIGN

In the following, the status of the design of the X-band based XFEL for hard X-rays will be summarised. The soft X-ray version and the options for the extension of existing facilities are not covered in this document.

Machine Layout and Fundamental Parameters

The layout of the X-band XFEL consists of the same principle elements as employed by all operating FEL facilities and is depicted in Fig. 2. An S-band gun creates a low-emittance (<0.3 μm) electron beam with a bunch charge of 250 pC. This bunch is accelerated with an S-band injector to an energy of 0.3 GeV and is then compressed in the bunch compressor BC1 to a length of about 44 μm . An X-band linearizer upstream of BC1 is used to correct distortions of the longitudinal phase space before the compression. Alternatively, designs employing an X-band gun and/or an all X-band injector are also being studied. After BC1 the electron bunch is accelerated with X-band accelerating structures to an energy of 2.24 GeV before it is compressed in BC2 to a bunch length below 8 μm . Then the bunch is further accelerated to its final energy of 6 GeV and fed into in-vacuum permanent magnet undulators, where X-rays with a nominal wavelength of 1 \AA are produced (tuning is not discussed here). The X-ray beams are guided via photon beamlines into the experimental area, where they are focusing and used in a variety of different instruments. The most important parameters are summarised in Table 1.

Injector

Two different types of injectors have been considered: (i) a 2.6 cell photo cathode RF gun operating at 3 GHz with 100 MV/m peak accelerating field similar to the Swiss-FEL [10], and (ii) a 5.6 cell photo cathode RF gun operating at 12 GHz with a maximum 200 MV peak accelerating field, which is similar to the one being developed at SLAC [11]. To extract charge from the cathode, we assumed a 9 ps full width half maximum (FWHM) laser pulse length for the S-Band gun, and a 3 ps FWHM laser pulse length for the X-band gun. For both types of RF guns the cathode is assumed to deliver 250 pC bunch charge. After the extraction, the beam is accelerated to 100 MeV by using either S-band traveling wave accelerating structures that are operating with a gradient of 20 MV/m at 3 GHz, or X-band traveling wave accelerating structures that are identical to the main linac structures operating with 65 MV/m gradient at 12 GHz. We have used the Poisson/Superfish code [12] to make a preliminary design for both, the gun and the generated field maps. The Astra code [13] has been used for the simulations performed to optimise the injector section. The beam sizes and emittances along the S-band and X-band based injectors are given in Fig. 3. As it can be seen, the projected normalised emittance ϵ_x is about 0.25 mm.mrad and 0.5 mm.mrad for the S-band and X-band based design.

Linac

The linac design process has proceeded through three main steps: RF parameters definition, longitudinal phase-space setup, and beam transport optimization. In the first step, the parameters of the acceleration structure and the RF unit were optimised in collaboration with the RF experts. The parameters (see RF section for details) were chosen to minimise the linac cost, while keeping the impact of transverse the wakefields at an acceptable level. Defining the parameters of the accelerating structure allowed to design and optimize the longitudinal phase space evolution along the machine. As it is expected that an X-band machine exhibits high sensitivity to RF stability [14], a semi-numerical optimization has been used, where analytical expressions of the sensitivities have been derived and used as figures of merit for a numerical minimization. This generated a layout that is "robust by design". The transverse beam transport has been provided with a lattice where the optimal balance between transverse focusing and transverse wakefield effects is achieved. Also a design entirely based on X-band components, i.e. using an X-band gun and injector (described in the injector section) is under study. Tests of beam-based alignment, using Dispersion-Free Steering and Wakefield-Free Steering have been performed with the PLACET tracking code [15]. The average emittance of 100 simulated machines (per line) with 100 μm RMS misalignment of the elements is depicted in Fig. 4, where each machine has been corrected using beam-based alignment (BBA), assuming a 5 μm BPM resolution. The tests confirm that the emittance growth can be kept below 0.03 μm in both axes, as shown in Fig. 4.

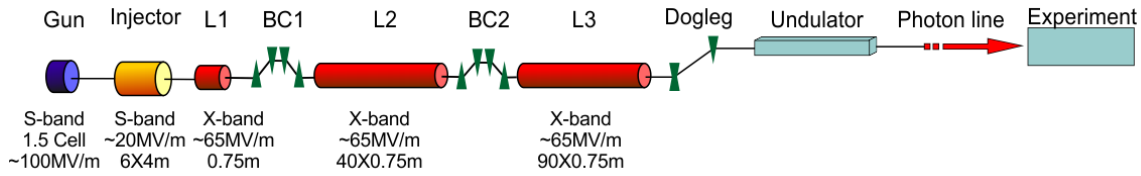


Figure 2: Schematic view the X-band XFEL for the S-band injector option.

RF Design

Based on an optimisation considering wakefield effects (described in the linac section), an optimal structure has been found with the following parameters: 72 cells, 0.75 m long, a/λ of 0.12, and a gradient of 65 MV/m. Ten of these structures will be installed on one RF module and will be fed by one RF station. This RF station consists of commercially available klystrons, modulators and pulse compressors (see Fig. 5). In the baseline option, two klystrons VKX-8311A from CPI will be driven by individual modulators K2-3 from Scandinova and will produce a 1.5 μ s long RF pulse. Two of these pulses will be added by a hybrid combiner to a 1.5 μ s pulse of 100 MW, which is then compressed to a 150 ns pulse via a pulse compressor. After this compression the 418 MW RF pulse is distributed via an RF network to the ten structures, which results in an acceleration gradient of 65 MV/m. With this option a repetition rate of 100 Hz can be reached. An alternative option, which is currently studied, is to power each structure with an individual 6 MW tubes E37113 from Toshiba and the modulator K2-1 from Scandinova. The RF pulses of length of 5 μ s also would have to be compressed with a pulse compressor. This option would allow to operate with an increased repetition rate of up to 400 Hz with approximately the same installation cost, but with lower energy efficiency.

Bunch Compressors

The baseline X-band FEL collaboration design includes a 2-stage bunch compression scheme. Harmonic lineariza-

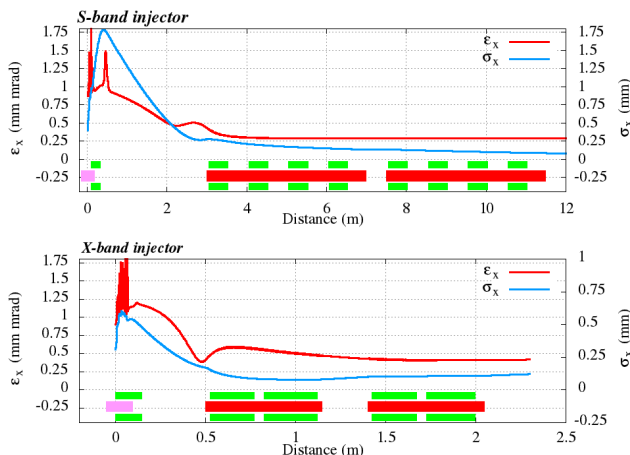


Figure 3: Emittance and beam size evolution along the S-band (top) and X-band (bottom) based injector.

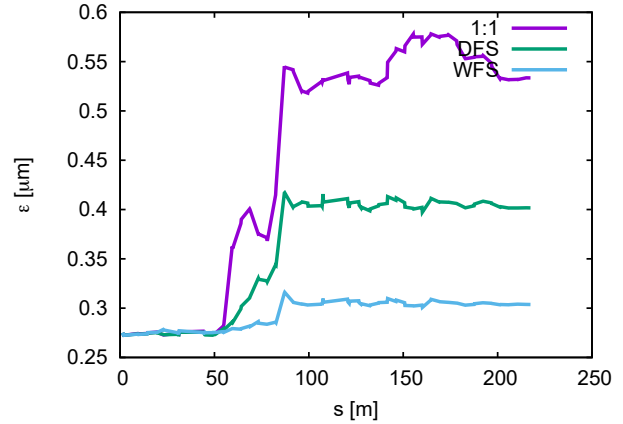


Figure 4: Horizontal normalised emittance along the FEL linac after beam-based alignment.

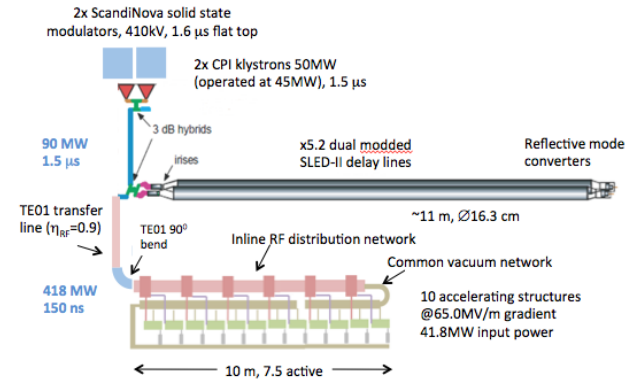


Figure 5: Schematic view of proposed RF unit (module).

tion is utilized through an S-band injector followed by a 12 GHz linearizing structure positioned just before the first chicane. This scheme allows of an overall compression ratio of 100 to be achieved, corresponding to a final bunch length of 26.7 fs. Figure 6 shows the Elegant [16] simulation results of the longitudinal phase space at the beginning and end of the first bunch compressor (BC1) and second bunch compressor (BC2). Alternative compression schemes are also being considered, including Optical linearization and Phase Modulation Linearization [17] employed with a dogleg compressor, for an all X-band machine.

Undulator Section

The baseline design for the undulator sections consists of 13 permanent magnet undulators of 3.96 m in length, with a

magnetic period length λ_u of 15 mm [18]. The modules are separated by gaps of 0.72 m to provide space for quadrupole magnets, beam position monitors, beam loss monitors and phase shifters. The maximal undulator parameter K of 1.3 results in an X-rays wavelength of 1 Å for a 6 GeV electron beam. The beam size is controlled in the undulator section with quadrupole magnets that form a FODO lattice. Since there is also weak focusing from the undulator magnets present, the quadrupole magnet strengths have been adapted in order to restore a regular β -function of the specified magnitude. This results in slightly different strengths for the focusing and the defocusing quadrupoles. The evaluation of the expected FEL performance relies mainly on numerical simulations with the codes GENESIS [19] and GINGER [20]. Using electron beams with the target parameters given in Table 1, the predicted X-ray output power is about 1 GW and 9 GW for seeded and SASE operation, respectively. The saturation length is about 37 m including the gaps. The output power can be increased with different tapering options, as shown in Fig. 7. Besides tapering, also the effect of energy detuning has been investigated. The undulator team works in close collaboration with the linac and bunch compressor group to optimise the quality of the produced electron bunches with respect to the produced output power via integrated simulations. An on-going effort is the determination of the mechanical and electrical tolerances of the undulator magnets and phase shifters.

UNDULATOR TECHNOLOGY DEVELOPMENTS

Undulator technology continues to make advances and FELs are able to take advantage of these improvements. The use of in-vacuum undulators has already been adopted by SACLA and SwissFEL, rather than out of vacuum technology. This enables shorter periods to be used, compared with standard out of vacuum undulators, and so lower electron beam energies, for the same output wavelength, are required.

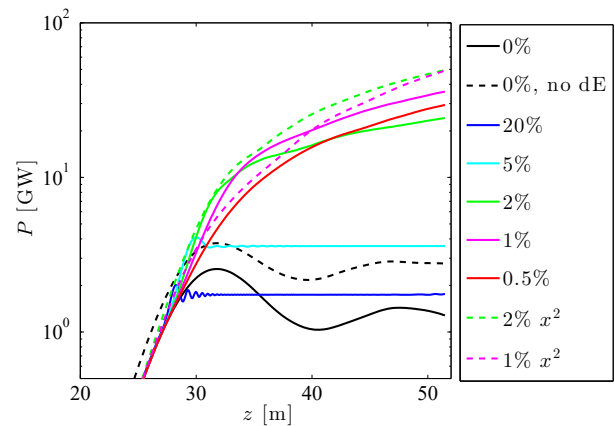


Figure 7: X-ray output power for different tapering options (here for seeded operation). For more details see [18].

The additional cost to the project of employing in-vacuum undulators instead of out of vacuum undulators is more than compensated for by the savings generated (in both capital and operating costs) by this lower electron energy requirement. This general approach of investing more in the undulator technology in order to make cost savings elsewhere in the facility appears to hold true for the other two technologies which we are considering: cryogenic permanent magnet undulators and superconducting undulators.

Cryogenic permanent magnet undulators (CPMUs) have been implemented in several 3rd generation storage rings [21–24] but not yet in a FEL. The advantages of operating at low temperature with NdFeB (~ 140 K) or PrFeB (77 K) are the much increased coercivity and 20% higher remanence. This allows for further reduced magnet period compared with in-vacuum undulators. An issue with both CPMU and in-vacuum undulators is that the output wavelength is varied by changing the magnet gap, and this then alters the resistive wall wakefield experienced by the electron bunch. It is possible that this could affect the electron bunch properties sufficiently that the beam will need to be retuned to optimise lasing. The alternative to gap tuning is beam energy tuning which obviously requires beam retuning as well. This issue may be an operational advantage for not just out of vacuum undulators but also superconducting undulators, which typically have a fixed aperture vessel for the electron beam and vary their magnetic field by changing the current in the coils. Superconducting undulators (SCUs) are not as mature as CPMUs but several groups are actively pursuing different designs and two storage rings have implemented them so far [25,26]. SCUs have the potential to generate the strongest fields of all the undulator technologies and so even shorter periods can be implemented whilst still maintaining reasonable tuning ranges. Typically SCUs employ NbTi wire but even stronger fields will be achieved if Nb₃Sn can be implemented. The advantages of SCUs for FELs is so significant that a dedicated R&D collaboration has been established for the LCLS-II project [27]. We plan to consider each of the

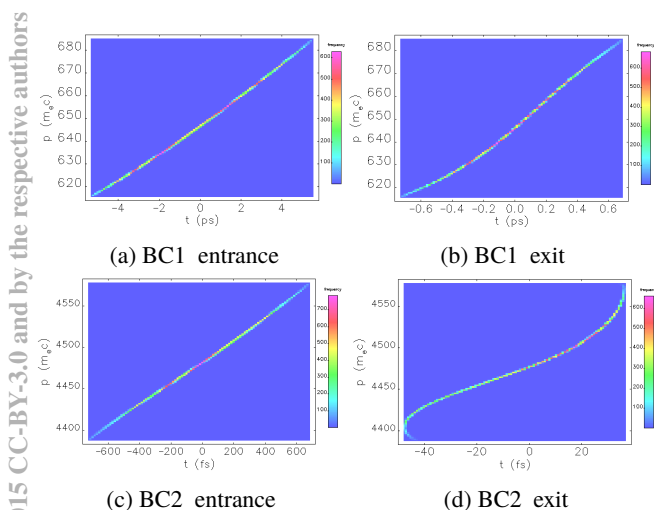


Figure 6: Longitudinal phase space evolution, through the two bunch compressors.

above undulator technologies from a facility cost perspective to establish the optimum facility parameters for each technology. Clearly the smallest possible undulator period results in the lowest electron energy requirements but this is not necessarily the optimum choice as the K parameter may well be too small and hence the gain length too long and also the wavelength tuning range from the adjustment of K (and not beam energy) may be unacceptable for the user.

PROPOSED TEST FACILITY AT CTF3

CALIFES is a 200 MeV electron linac [28], which is part of the CLIC Test Facility 3 (CTF3) at CERN. The linac is capable of producing an electron beam with a wide range of parameters. Of particular note are the low emittance (2 mm mrad), short bunch length (down to 300 μm), and range of bunch charge capabilities (up to 1.5 nC), available in single- or multi-bunch trains (up to > 100 bunches at 1.5 GHz). After the planned CTF3 shutdown at the end of 2016, the community has proposed to convert CALIFES into an advanced test facility for X-band FEL applications, as well as other users. The CALIFES linac is located close to the existing high power X-band RF test-stands [29] which can be used to power X-band structures.

Tests with beam are needed to demonstrate that sufficiently high peak current and good beam quality can be obtained with X-band. In CALIFES a number of X-band components can be tested, including phase-space linearizers, transverse deflecting cavities (for bunch length diagnostics and RF spreaders) and wakefield monitors. CALIFES would also provide an opportunity to test novel bunch compression schemes including purely magnetic compression systems. CALIFES would be the only facility in Europe where a significant amount of time could be dedicated to X-band tests, until the completion of CLARA at Daresbury.

CONCLUSIONS

The X-band FEL collaboration is a group of 12 institutes and universities that works jointly towards the design of an X-ray FEL based in X-band acceleration technology. The advantage of the X-band technology is that the linac can be much shorter, due to the higher achievable gradients. This reduces the overall cost of the facility, which could in the future increase the availability of coherent X-rays for the user community. Due to the combined efforts, the design studies are progressing rapidly, as reported in this paper. The collaboration also follows closely the developments in the undulator sector, since technological advances in this area have the potential to further reduce the cost of a proposed facility. There are also plans to use the existing electron linac CALIFES at CERN to test FEL technologies that are of relevance for the collaboration. As a long-term goal, the efforts of the X-band FEL collaboration will hopefully grant more users the access to the highly demanded, high-brightness, coherent X-ray beams.

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