X-BAND TECHNOLOGY FOR FEL SOURCES

G. D'Auria, S. Di Mitri, C. Serpico, Elettra-Sincrotrone Trieste, Italy.
N. Catalan-Lasheras, A. Grudiev, A. Latina, D. Schulte, S. Stapnes, I. Syratchev, W. Wuensch, CERN, Geneva, Switzerland.
A. Aksoy, Ö. Yavaş, Institute of Accelerator Technologies, Ankara, Turkey.
M. J. Boland, T. Charles, R. Dowd, G. LeBlanc, Y.-R. E. Tan, K. P. Wootton, D. Zhu, Australian Synchrotron, Clayton, Australia.
D. Angal-Kalinin, J. Clarke, STFC, Daresbury Laboratory Cockcroft Institute, Daresbury, UK.
M. Jacewicz, R. Ruber, V. Ziemann, Uppsala University, Uppsala, Sweden.
W. Fang, Q. Gu, Shangai Institute of Applied Physics, Shanghai, China.
E. N. Gazis, National Technical University of Athens, Greece.
C. J. Bocchetta, A. Wawrzyniak, Solaris, Jagiellonian University, Krakow, Poland.
E. Adli, University of Oslo, Norway.
G. Burt, Lancaster University, Lancaster, UK.
X.J.A. Janssen VDL ETG T&D B.V., Eindhoven, Netherlands.

Abstract

As is widely recognized, fourth generation Light Sources are based on FELs driven by Linacs. Soft and hard X-ray FEL facilities are presently operational at several laboratories, SLAC (LCLS), Spring-8 (SACLA), Elettra-Sincrotrone Trieste (FERMI), DESY (FLASH), or are in the construction phase, PSI (SwissFEL), PAL (PAL-XFEL), DESY (European X-FEL), SLAC (LCLS II), or are newly proposed in many laboratories. Most of the above mentioned facilities use NC S-band (3 GHz) or C-band (6 GHz) linacs for generating a multi-GeV low emittance beam. The use of the C-band increases the linac operating gradients, with an overall reduction of the machine length and cost. These advantages, however, can be further enhanced by using X-band (12 GHz) linacs that operate with gradients twice that given by C-band technology. With the low bunch charge option, currently considered for future X-ray FELs, X-band technology offers a low cost and compact solution for generating multi-GeV, low emittance bunches. Furthermore, X-band accelerating structures are also becoming widely used for extremely high brilliance e-sources, beam phase space manipulation and very accurate beam diagnostics.

The paper reports the ongoing activities in the framework of a collaboration among several laboratories for the development and validation of X-band technology for FEL based photon sources.

INTRODUCTION

Applications of X-band technology is rapidly expanding due to its great potential already shown in different areas of particle accelerators. Early studies on accelerating structures operating at 11.4 GHz were made at SLAC/KEK, in the last two decades of the last century (up to 2004), for the development of a TeV-scale high energy Linear Collider, and led to achieve 65-70 MV/m accelerating gradients [1]. Later, significant progress have been achieved by the CERN CLIC (Compact Linear Collider) Collaboration, that has recently demonstrated the possibility to operate 12 GHz accelerating structures with an average loaded gradient higher than 100 MV/m [2], values far beyond those reached with the present S and C band technology. These results suggest that the X-band may represent a useful solution to get very compact and cost effective linacs for multi-GeV electron beams. Considering operation at the above mentioned gradients, a 1 GeV X-band linac can be easily housed in less than 20 m, a very attractive solution even for application with a limited space availability [3]. More recently, after the successful operation of the new FEL light sources like LCLS, SACLA, FERMI, a stronger and more vigorous interest in X-band technology has arisen.

The demand for new FEL facilities is worldwide continuously increasing, spurring plans for new dedicated machines [4]. This led to a general reconsideration of costs and spatial issues, particularly for the hard X-ray sources, driven by long and expensive multi-GeV NC linacs. For these machines the use of X-band technology can greatly reduce cost and capital investment, reducing the linac length and the size of buildings. To pursue these objectives, a scientific collaboration has recently been established among several laboratories, interested in FEL developments, aimed at validating the use of X-band technology for FEL based light sources [5]. Other Institutions, like CERN, with no specific interest in FEL physics, are within the collaboration for its positive impact on the CLIC project. The specific objectives of the collaboration will include the design, assembly and high power tests of an X-band accelerating module for FEL applications, made up of two accelerating structures, RF pulse compression and a waveguide distribution systems. Special care will be given to the operating gradients, RF breakdown fault rate, alignment issues, wake fields, and operation stabilities. The overall objective of the collaboration is to support the feasibility studies of new research infrastructures and/or the major upgrading of existing ones, using X-band technology. The work program foresees a strong interaction between FEL scientists, FEL designers and accelerator experts. Starting from the FEL output specification, a fully self consistent FEL facility design will be established (in terms of

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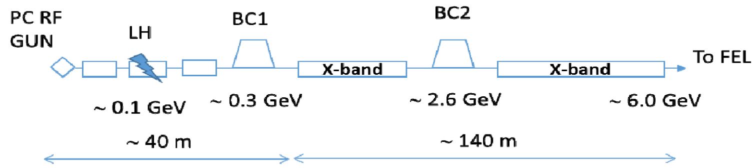

Figure 1: 6 GeV linac layout.

accelerator layout, major hardware choices, and FEL system design). Here two possible scenarios are briefly illustrated and discussed: the layout of a new hard X-ray FEL facility, with performance slightly different from those reported in [5] and one for the upgrading of an existing facility (i.e. FERMI FEL)

LINAC DESIGN

New Hard X-ray FEL Source

A 6 GeV linac layout is proposed in Fig. 1 to drive a 0.16 nm SASE FEL [6], whose estimated output performance is listed in Tab.1. The electron beam injector is assumed to be a standard RF photo-cathode Gun followed by S-band accelerating structures up to the energy of ~285 MeV. Here the beam enters the first magnetic chicane for bunch length compression (BC1) with the following characteristics: 200 pC beam charge, 2.5 ps RMS duration, 0.15 µm rad transverse normalized emittance (slice and projected), 15 keV RMS uncorrelated energy spread as in the presence of beam heating [7]. An X-band cavity linearizes the compression [8]. After BC1, only X-band accelerating structures are foreseen, each one 0.8 m long and a maximum accelerating gradient of 60 MV/m. Each klystron supplies 4 structures (one "module"). The modules are interleaved by quadrupole magnets to build a FODO-like optics. The X-band linac total length is approximately 120 m, 100 m being the RF active length. Tab. 2 summarizes the linac and the compressor parameters.

Table 1. FEL expected performance.

Undulator period	30	mm
Undulator parameter	1	
Fundamental wavelength	0.16	nm
Pierce parameter	0.1%	
3-D Gain length	1.7	m
3-D Saturation length	~ 40	m
Peak power at saturation	9	GW

Table 2. Linac and compressor parameters

Linac length downstream BC1	50	m
Linac length downstream BC2	70	m
Energy at BC1	0.285	GeV
R_{56} in BC1	-38	mm
Energy at BC2	2.630	GeV
R_{56} in BC2	-14	mm
Compression factors	12.5 × 5.5	m

The two-stage compression scheme is arranged with the following prescriptions: i) RF phase not larger than -30 deg X-band far from the crest, to limit the impact of phase jitter on linac and FEL performance; ii) total energy spread at the compressors < 2% RMS, to limit beam emittance degradation by chromatic aberrations; iii) dipole magnetic field in the compressors < 1 T; iv) use of geometric longitudinal wakefields (short-range) in the last linac modules to remove the energy chirp required for upstream compression. After BC2, the linac can be run on-crest to maximize the final energy. The transverse and longitudinal geometric wake functions for the X-band structures were estimated with Bane's model [9] for a cell iris radius of 3.75 mm. The longitudinal dynamics was established with LiTrack [10] to ensure final peak current (1.5 kA) and RMS energy spread (<0.1%) suitable for lasing, see Fig. 2. The degradation of the projected emittance by coherent synchrotron radiation and transverse wakefield instability was estimated with an analytical model [11], as shown in Fig. 3.

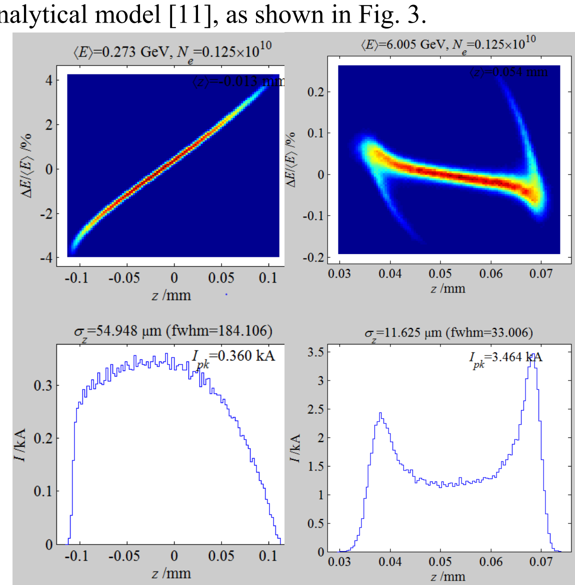

Figure 2. Longitudinal phase space (top) and current profile (bottom) at the exit of BC1 (left) and linac end. The RMS energy spread is, respectively, 1.8% and 0.05%.

FERMI FEL Upgrading

FERMI is a soft X-ray, fourth generation light source facility in operation at the Elettra Laboratory in Trieste, Italy [12]. It is based on a seeded FEL, driven by a NC linac operated up to 1.5 GeV. Two different FEL lines produce short coherent photon pulses in the UV and soft X-ray region (80-4 nm): FEL1 covers the spectral range 80-20 nm, FEL2 20-4 nm [13]. The two lines are not operated simultaneously. The beam is optimised from time to time for the operation of one of the two FELs. A real breakthrough would be provided by two sources which can simultaneously be used for experiments, where one of the sources is used as a pump to create specific excited states and the other as a probe of the evolving transient states. Stimulated by the high interest expressed from the users community, a proposal aiming at studying the possibility of extending the FERMI infrastructures, to include a third FEL beamline (FEL3), which can work together with the existing two, is being evaluated.

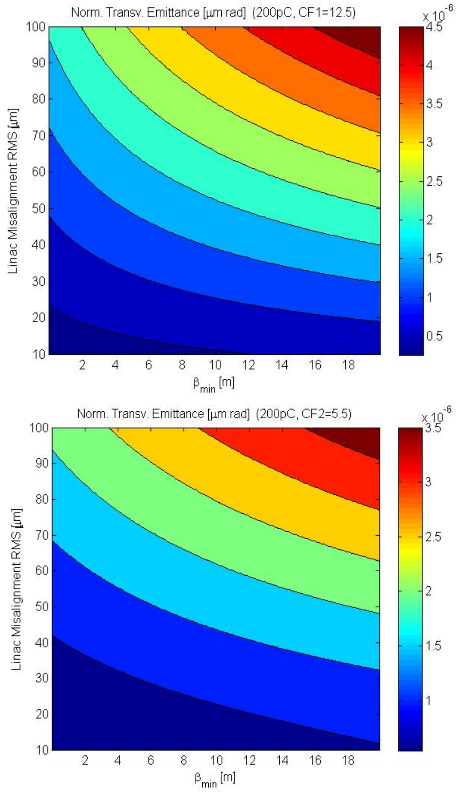

Figure 3. Normalized RMS projected emittance at the entrance of BC2 (top) and linac exit (bottom), as function of the linac-to-beam RMS misalignment and the horizontal betatron function in the BC1 (top) and BC2. The plot on the top assumes an initial emittance of 0.15 μm, the plot on the bottom 0.5μm.

FEL3 should address photon wavelength up to 0.5 nm, see Tab. 3, with the apparent advantage to provide two independent pulses with different colours, allowing simultaneous running of two experiments and expanding the research opportunities using much shorter wavelengths.

Table 3. FEL3 expected performance.

Undulator period	30	mm
Undulator parameter	1	
Fundamental wavelength	0.5	nm
Pierce parameter	0.11%	
3-D Gain length	1.6	m
3-D Saturation length	26	m
Peak power at saturation	5.6	GW

Accessing this wavelength range would require an increased energy from the linac. Such a beam energy upgrade can be reached adding a new linac segment in the high energy region of the present machine, as sketched in Fig. 4. Considering the current situation, it is possible to go beyond 3.5 GeV, adding a 50 m X-band linac, operated at 65-70 MV/m, using infrastructures and spaces already available. A detailed study of the linac configuration, the FEL source parameter optimization and an estimate of the expected FEL performances will be addressed later. Considering to maintain the two sources simultaneously in operation and synchronized for pump and probe experiments would constitute a unique world opportunity for a class of experiments that could not be done at any other facility. This needs implementing new concepts for splitting and controlling the timing that should go down to the ns time scale. Particular attention will be given to the possibility of synergy between the two sources, preserving the possibility of their simultaneous use.

The peculiarity of this ambitious proposal is that the new machine layout will leave unchanged the total length of the present tunnel and can be implemented using a progressive approach, minimizing cost and impact on the facility. Furthermore, it is important to point out that it can be pursued only by exploiting the X-band technology potential and high gradient structures.

CONCLUSION

The successful operation of the forth generation light sources has generated worldwide interest for this new and very powerful investigation tool. Research programs based on X-ray FELs and plans to develop and build new facilities are currently underway in many laboratories. However, accessing these research tools ask for large investment costs, increasingly important for hard X-ray machines driven by long multi-GeV linacs. This requires a joint effort to validate different schemes and technologies to make accelerators more compact, less expensive and increasingly available. An International Collaboration, gathering different laboratories has been established aiming at validating X-band technology as an alternative to the present configurations, making it widely available for future implementations.

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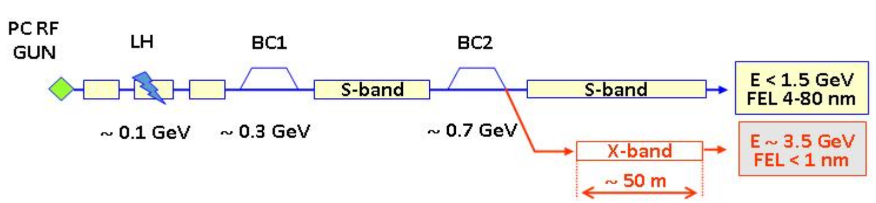

Figure 4: FERMI upgraded layout.

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