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Compact Electron Linacs for Research, Medical, and Industrial Applications

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The CLIC study has developed compact, high-gradient, and energy-efficient acceleration units as building blocks for a future high-energy, electron-positron linear collider. The components to construct such units, including RF sources, are now generally available in industry and their properties promise cost-effective solutions for making compact electron-based linacs (already a crucial technology in many research, medical, and industrial facilities) more efficient and compact. The CLIC study has actively promoted and supported spin-off developments for a decade. Examples include beam manipulation and diagnostic devices in research linacs, including Free-Electron Laser light sources; compact inverse Compton scattering X-ray sources; medical linacs, including FLASH radiotherapy; and compact neutron sources for material investigations. This paper describes the X-band technologies developed as part of the CLIC study and discusses examples of compact linacs utilising such technology for different applications.

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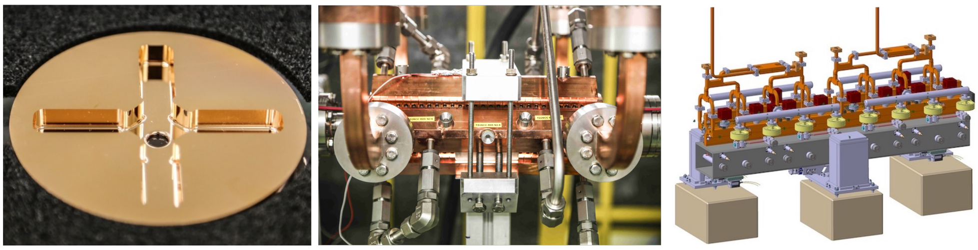
1. Introduction

CLIC (Compact Linac Collider) is a next-generation, linear e^+e^- collider with a staged implementation plan for operation at 380 GeV, 1.5 TeV, and 3 TeV centre-of-mass energies with an expected luminosity of $2.3 \times 10^{34}\,\mathrm{cm}^2\mathrm{s}^{-1}$ for the first stage [1]. CLIC has undergone technical R&D for over three decades and essential to its proof-of-concept has been the development of the design, production, conditioning, and operating processes of high-gradient, high-efficiency, X-band (11.994 GHz) accelerating structures as well as the RF technologies needed to drive them. These high-gradient structures are designed to operate at 100 MV/m with a minimum breakdown rate and can also be utilised for more compact and cost-effective electron linacs in smaller-scale applications.

Part of the CLIC R&D strategy has been to spin-off and promote the industrial base and adoption of high-gradient technologies in the research, medical, and industrial sectors. This paper outlines the X-band RF technologies developed as part of the CLIC studies before highlighting examples of high-gradient adoption by both current and future facilities.

2. High-gradient CLIC technologies

Figure 1 shows the components of a CLIC X-band accelerating module [2]. It begins with the fabrication of individual accelerating cells (Fig. 1a) that require ultra-precision machining to within micrometer-level tolerances. Several tens of cells are then precisely assembled into an accelerating structure (Fig. 1b) in brazing furnaces. These accelerating structures are then conditioned and tested in test-stands before being integrated with the necessary infrastructure (including vacuum, cooling, and mechanical components) and an optimised RF power system and distribution network to create an accelerating module (Fig. 1c).



(a) Accelerating cell. **(b)** Accelerating structure. **(c)** Accelerating module.

Figure 1: The components of a CLIC accelerating module.

Figure 2 shows components of an RF power module required to drive a klystron-based CLIC accelerating module [3]. A modulator (not pictured) provides high-voltage to a 50 MW X-band klystron (Fig. 2a) whose peak output power is increased by a barrel open cavity (BOC) pulse compressor. An RF power network (Figs. 2b and 2c) distributes the power to the accelerating module and drives the accelerating structures. The accelerator and RF power modules are the building blocks for the klystron-based CLIC design.

A major boost to the development, consolidation and implementation of a CLIC-like klystron-based module was provided by the Horizon 2020 EU project ‘CompactLight’ [4], where an international collaboration of 35 institutes developed the conceptual design of an X-ray FEL

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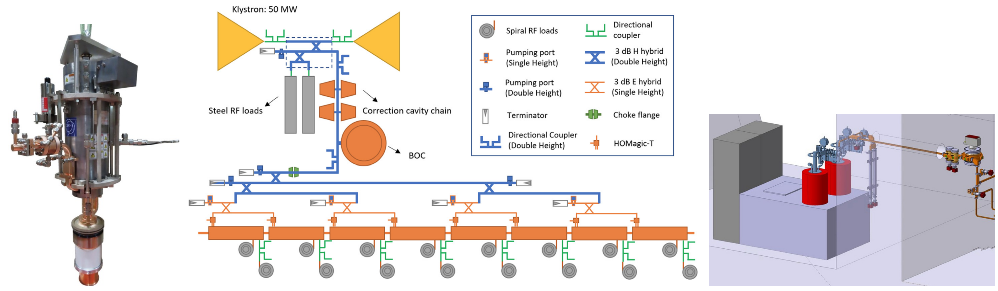

(a) Klystron. **(b)** RF power network [3]. **(c)** RF power module [3].

Figure 2: Components of a CLIC RF power module. Klystron image courtesy of CETD, Japan.

light source based on high-gradient X-band accelerator structures. Using X-band, CompactLight could reduce the overall footprint and significantly reduce capital and operating costs compared to conventional FELs while enabling operation at kHz repetition rates. The linac of the EuPRAXIA@SPARC_LAB [5] project is based on the CompactLight X-band module.

The compactness and power efficiency of high-gradient structures make them an attractive option for compact electron linac design. This not only enhances particle accelerator design in well-established applications but also facilitates original applications that are unfeasible with lower gradient technology.

3. Applications and examples of high-gradient technology

Table 1 lists high-performance linacs and beam test stands that utilise high-gradient accelerating cavities in a diverse range of applications. We highlight a few in further detail.

CERN is collaborating on two medical applications involving compact electron linacs. The first is STELLA [6], which aims to design and deploy robust, modular, smart, and affordable 6 MV radiotherapy (RT) treatment machines that are optimised for tackling the regional and global inequities in access to RT. The integration of a high-gradient, high-capture accelerating structure not only compactifies the design but also reduces the strain on the electron gun and ultimately the downtime associated with its failure. The second involves FLASH-based RT, which appears as a promising and tantalising technique for treating cancer in fewer fractions (corresponding to fewer hospital visits) and with lessened side effects. Deep-seated tumours can be treated with very high energy electrons (VHEE) of 50 MeV – 250 MeV, and the DEFT [7] facility exploits high-gradient, X-band technology to fit within a hospital campus and budget.

CERN has also collaborated on the experimental testing and accelerator design of VULCAN [8], a 35 MeV electron-driven, pulsed, cold neutron source optimised for neutron diffractometry measurements in an industrial environment. By utilising high-gradient technology, the accelerator is just a few metres in length and also very efficient, optimising the conversion of the wall plug power required to accelerate the electrons into the desired cold neutrons.

ICS sources collide electrons with energies in the range of 10s MeV – 100s MeV with a laser to create brilliant, monochromatic and tunable X-ray sources. By exploiting high-gradient accelerating technology, ICSs can fit in an industrial setting. Smart*Light [9] is an example of a 'tabletop' ICS.

Spin-off applications of CLIC accelerating structures are not just limited to high-gradient acceleration. For example, many FELs operating at S- and C-band utilise X-band accelerating

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Table 1: A non-exhaustive* list of high-performance linacs and beam test facilities utilising high-gradient technology. The f-band column gives the frequency band of the linac accelerating structures. The application column is abbreviated as: UF = user facility, TF = beam test facility, ICS = inverse Compton scattering X-ray source, XFEL = X-ray free electron laser, PD = plasma accelerator drive beam, I = injector, VHEE-F = very high electron energy FLASH, RT = radiotherapy, NS = neutron source, HEP = high-energy physics.
*This list of current and planned high-performance linacs and beam test stands (as well as a list of high-gradient test stands, linearisers and deflectors) is actively collated by walter.wuensch@cern.ch.

Linac	Host Laboratory	Application	f-band	Status
ARES [11]	DESY, Germany	UF	S	Operational
CLARA [12]	Daresbury Lab., UK	UF	S	Commissioning
CLEAR [13]	CERN, Switzerland	UF, TF	S	Operational
NLCTA [14]	SLAC, US	TF	X	Operational
CXLS [15]	ASU, US	ICS	X	Operational
Smart*Light [9]	TU/e, Netherlands	ICS	X	Operational
TTX-II [16]	Tsinghua Uni., China	ICS	X	Operational
VIGAS [17]	Tsinghua Uni., China	ICS	X	Constructing
CompactLight [4]	EU Collaboration	XFEL	X	Design Study
CXFEL [18]	ASU, US	XFEL	X	Constructing
FERMI 2.0 [19]	Elettra, Italy	XFEL	S	Constructing
SACLA [20]	RIKEN, Japan	XFEL	C	Operational
SwissFEL [21]	PSI, Switzerland	XFEL	C	Operational
SXFEL [22]	SSRF, China	XFEL	C	Operational
EuPRAXIA [5]	INFN Frascati, Italy	XFEL, PD	X	Procuring
AWAKE (RUN2) [23]	CERN, Switzerland	PD	X	Procuring
NewSUBARU [24]	Riken, Japan	I	C	Operational
DEFT [7]	CHUV, Switzerland	VHEE-F	X	Procuring
SAFEST [25]	Sapienza, Italy	VHEE-F	C	Prototyping
STELLA [6]	Daresbury Lab., UK	RT	S	Design Study
VULCAN [8]	DAES SA, Switzerland	NS	S	Design Study
C^3 [26]	SLAC, US	HEP	C	Design Study
CLIC [1]	CERN, Switzerland	HEP	X	Design Study
eSPS [27]	CERN, Switzerland	HEP	X	Design Study

structures to linearise the longitudinal phase space of the electron bunches and ultimately enhance the FEL brilliance [2]. In addition, the development of PolariX [10] (an X-band transverse deflector) allows for the sub-fs time resolution of an electron bunch alongside the ability to resolve beam properties in different transverse directions.

4. Conclusion

The knowledge, skills, and expertise gained in developing normal-conducting, high-gradient, X-band accelerating structures with a minimised breakdown rate for the CLIC project has had a very positive 'trickle-down effect' on the adoption and utilisation of high-gradient and X-band structures in compact electron linacs for research, medical, and industrial applications. Not only does this enhance the industrial base for producing such equipment but also widens the door for enhancing and enabling a diverse range of particle accelerator applications that have immediate and obvious benefits to society.

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