PROCEEDINGS OF SCIENCE

CLIC X-band technology developments and their use in compact accelerators for research, medicine and industry.

S. Doebert for the CLIC collaboration[a,*]

[a] *CERN,*
Esplanade des Particules 1, Geneva, Switzerland

E-mail: steffen.doebert@cern.ch

The CLIC study has developed compact, high gradient and energy efficient acceleration units as building blocks for a high energy linear collider for high-energy physics. Many of these components are now available in industry. These properties promise cost effective solutions for small linear accelerators in a variety of applications. The CLIC study actively promoted and supported such spin-off developments from the beginning. The applications include beam manipulation and diagnostic in research linacs such as FEL light sources, compact Compton-scattering x-ray sources, medical linacs for cancer treatment and compact neutron sources for material investigations. This contribution will introduce the developed x-band technologies developed and discuses examples of their use in some of the applications.

**** FIXME: Name of conference, ****
**** FIXME: day-day Month YEAR ****
**** FIXME: Location, City, Country ****

*Speaker

PoS(EPS-HEP2023)623

1. CLIC X-band technology

Today most electron accelerators in particular for industrial application use still S-band (3GHz) technology. The availability of ready to use components, like high power sources, accelerating structures, waveguide components and control electronics was the reason for this frequency choice. The origin of the frequency choice dates back to the radar developments in world war II. In the last 70 years however accelerator technology made of course huge progress and other frequency bands have been exploited for accelerator application in particular C-band (5-6 GHz) and X-band (11-12 GHz). Higher frequencies allow higher acceleration gradients and therefore more compact and cost effective accelerators. The power consumption scales inversely with frequency promising lower initial investment and operational cost. For the same reasons X-band has been chosen as the operating frequency for large scale particle accelerators for high energy physics. A number of studies have been conducted around the world, for example, the Next Linear Collider (NLC) at SLAC [1], Japanese Linear Collider (JLC) at KEK [2] and the Compact Linear Collider (CLIC) at CERN [3]. All these projects developed high gradient accelerating structures, x-band power sources and waveguide components now available for applications outside high energy physics. We will focus in this paper on the technologies developed by the CLIC collaboration and the related applications.

The CLIC collaboration developed x-band accelerating structure which can maintain an accelerating gradient of up to 100 MV/m with an excellent RF to beam power efficiency since the power consumption was a concern for the machine from the beginning. An example of a CLIC x-band structure can be seen in Figure 1. Many prototype structures have been built and tested around the world. CLIC developed and transferred to industry the know how of ultra-high precision machining with micrometer tolerances, the optimal surface treatment of the copper disks as well as the precise assembly in brazing furnaces. High power x-band klystrons have been developed with industry and are now available with output powers between 6 and 50 MW. A few tens of such klystrons are operational around the world. In addition numerous high power capable waveguide components have been developed, tested and licensed to industry. Therefore the essential building blocks of a state of the art x-band accelerator are available and accessible for potential new application in science, industry or medical. The CLIC collaboration promotes actively the use of its technology developments and provides help for their implementation as part of its R&D strategy. Today a large number of x-band installations are operating in accelerator institutes around the world either as part of operating machines or as test facilities, therefore a broad knowledge of using these components exists already world wide.

2. Examples of x-band applications

2.1 Applications for CLIC-technology in Science

Naturally the first applications outside the original linear collider scope have been realised in other fields of accelerator based science in particular in photon science. A number of Free Electron Lasers (FEL) operating at S- or C-band make use of X-band accelerating structure to linearize the longitudinal phase space enabling a better bunch compression which boosts the FEL performance in terms of light intensity [4]. Very popular are as well x-band transverse deflecting structures to

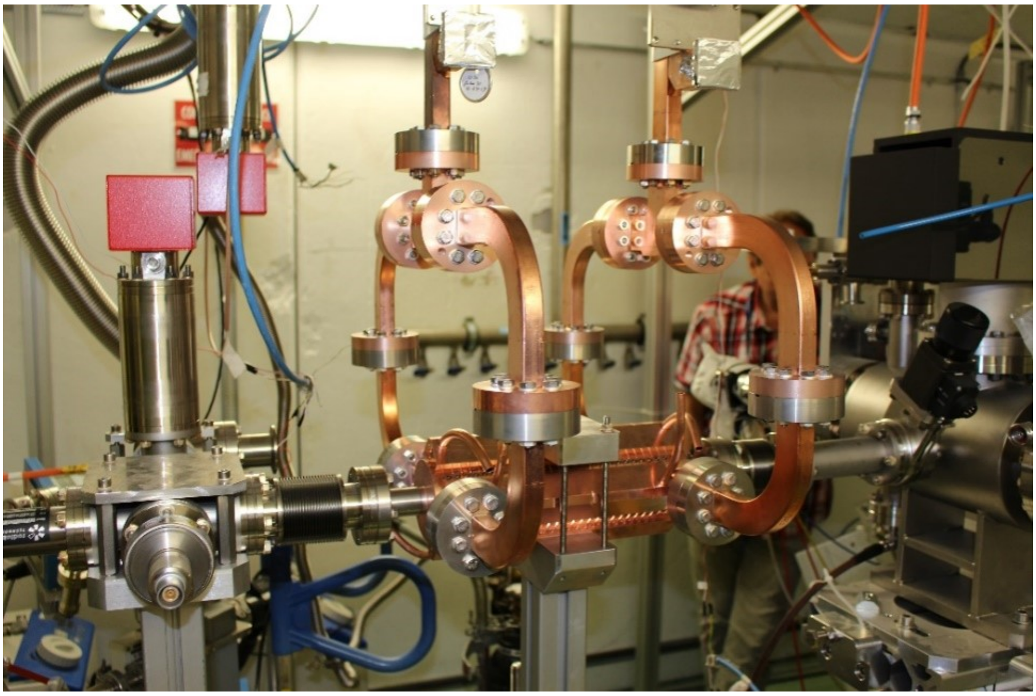

Figure 1: Photo of a CLIC type accelerating structure, able to work at a gradient of 100 MV/m with very low breakdown rate.

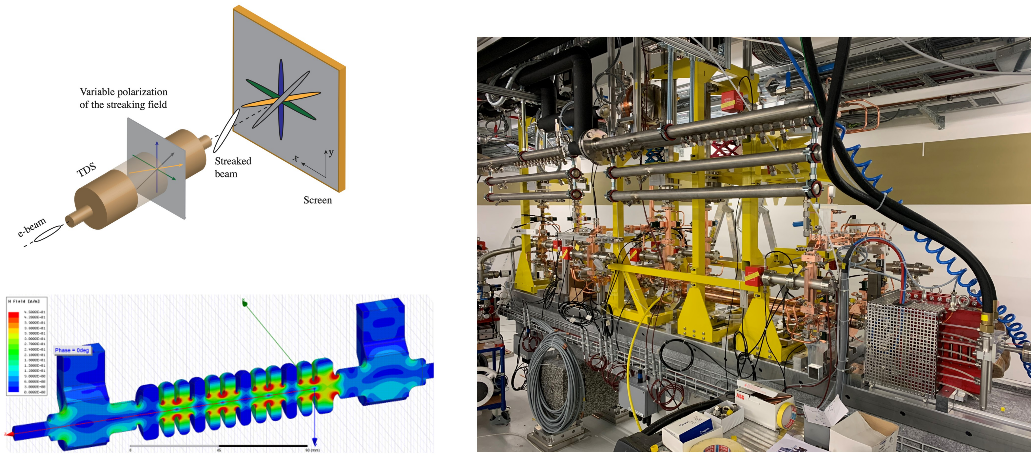

Figure 2: Schematic view (upper left), magnetic field distribution (lower left) and implementation example at the Paul Scherer Institut (right) of a PolariX x-band deflector structure

diagnose the longitudinal phase space which then helps again to optimise the machine performance. Those deflecting cavities (called PolariX), deflect the beam transversely but in a time resolved manner due to the high frequency which allows to study for example the slice energy spread of the electron bunches. The development of the PolariX structure is unique because by changing the polarisation of the incoming microwave the direction of the deflection can be changed [5]. An example of such a structure is shown in Figure 2.

X-band accelerators offering a higher gradient are as well a natural choice for energy-upgrades of existing linear accelerators with fixed space constraints. Many projects worldwide are investigating to exchange typically S-band linacs with gradients below 20 MV/m with x-band accelerators reaching up to 100 MV/m gaining a factor of 5 in energy reach within the same premises. A European funded design study called CompactLight [6] went further in designing an X-ray FEL from scratch using x-band technology. The study concluded that one can reduce the footprint of such a machine and realize savings of roughly a factor 2 compared to conventional FEL's in investment and operational cost. In addition the lower dissipated power of an x-band accelerator allows operation with kHz repetition rate which opens attractive new possibilities for users.

Another somewhat surprising active area of x-band applications is the field of advanced accelerator technologies using plasma wakefield acceleration. It turns out for laser driven plasma wakefield acceleration (LWA) which suffers typically from high energy spreads in the beams, an x-band structure in combination with a chicane can be used to mitigate this short come [7].

The European project EuPraxiaSparcLab [8] makes use of a compact 1 GeV X-band linac to demonstrate electron beam driven plasma wakefield acceleration (PWA). At CERN an x-band injector is used to inject the probe beam into a proton driven plasma wakefield acceleration experiment (AWAKE) [9].

2.2 Industrial applications of X-band technology

Besides the numerous applications of X-band technology in accelerator based science facilities there is an increasing interest in industrial type of applications. The compactness and potentially lower cost of such a machine makes it attractive for x-ray generators based on inverse Compton scattering (ICS). These sources collide a power full laser with an electron beam to generate a high brilliance x-ray source which has a tuneable line spectrum. This radiation is very attractive for material science, medical and cultural heritage investigations. The University of Technology in Eindhoven teamed up with the CLIC study to develope a very inovative table top ICS source called Smart*Light [10] for cultural heritage studies based on a CLIC type x-band accelerator. A DC electron gun is injecting into an x-band cavity which accelerates the beam to about 30 MeV and then collided with a laser beam in an interaction chamber (see figure 3). This facility has been build and is currently under commissioning with beam.

A higher energy photon source using x-band linac technology is being build at Tsinghua University in China aiming for a total electron energy of 350 MeV and gamma-ray production [11].

Another possibility for material investigations is the use of neutron beams which has a lot of industrial interest. CERN supports a project to develop a turn-key industrial compact neutron source in the framework of its CERN innovation program of environmental applications (CIPEA). This machine could be used in particular to study electrode erosion within modern car batteries [12].

Finally recent developments in radio therapy like FLASH therapy and very high energy electron therapy (VHEE) to treat deep seated tumors, call for compact, affordable linear accelerator systems. For this kind of application X-band technology seems ideal, combining high gradient with lower energy consumption. CERN developed together with the University Hospital of Lausanne (CHUV) a conceptual design for a 140 MeV x-band accelerator with VHEE and FLASH therapy capability called DEFT [13]. This machine is under construction.

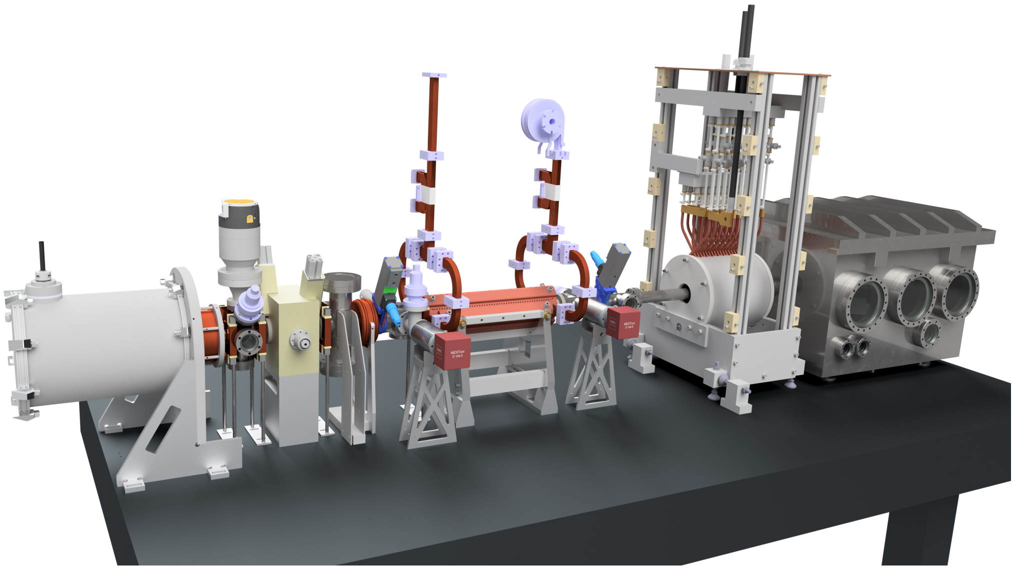

Figure 3: 3-D Model of the Smart*Light ICS source at Eindhoven University of Technology. A DC-electron source (left) injects directly into an x-band accelerator (center) to boost the electron energy to 30 MeV. A laser collides with the electron beam in an interaction chamber (right) to generate the x-rays.

3. Conclusion

The x-band technologies originally developed by normal conducting linear collider projects for high energy physics become increasingly attractive for small and medium scale accelerators in scientific, industrial and medical applications. This shows on one side the maturity of the developed hardware already existing and will on the other side widen the industrial base of such equipment. These new applications are very promising and represent an excellent spin-off from fundamental science into society relevant applications. In addition this is a welcome reward for our community while still waiting for the realisation of a linear collider originally triggering these technology developments. While the use of X-band technology for high energy physics is still awaiting the green light for a major project, many of the above mentioned applications have been already realized or are under construction.

References

[1] N. Phinney, "Next Linear Collider", SLAC-R-571, Stanford, 2001.

[2] "JLC Preport", KEK Report 92-16, Tsukuba, 1992.

[3] Aicheler, M and Burrows, P and Draper, M and Garvey, T and Lebrun, P and Peach, K and Phinney, N and Schmickler, H and Schulte, D and Toge, N, "A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report", CERN-2012-007, Geneva, 2012.

[4] G. D'Auria et al., "The X-band System for the FERMI@ELETTRA FEL Project", in Proc. 1st Int. Particle Accelerator Conf. (IPAC'10), Kyoto, Japan, May. 2010, TUPE015, pp. 2173-2175.

[5] Marchetti, B., Grudiev, A., Craievich, P. et al. "Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure". Sci Rep 11, 3560 (2021). https://doi.org/10.1038/s41598-021-82687-2.

[6] G. D'Auria et al., "XLS Deliverable D2.3: Conceptual Design Report of the CompactLight X-ray FEL," XLS-Report-2021- 010, Dec. 2021. doi:10.5281/zenodo.6375645.

[7] Pousa, A. Ferran and others, "Energy Compression and Stabilization of Laser-Plasma Accelerators, Phys. Rev. Lett.,Vol. 129, 094801, 2022

[8] M. Diomede et al., "Preliminary RF design of an X-band linac for the EuPRAXIA@SPARC-LAB project", Nucl. Instrum. Meth. Phys. Res. A vol. 909 (2018) pag. 243, doi: 10.1016/j.nima.2018.01.032.

[9] J.M. Arnesano, S. Döbert, "Design of an X-Band Bunching and Accelerating System for AWAKE Run 2", in: LINAC 2022, Liverpool, United Kingdom, 2022.

[10] X.F.D. Stragier, P.H.A. Mutsaers, O.J. Luiten, "Smart*light: A tabletop, high brilliance, monochromatic and tunable hard X-ray source for imaging and analysis", Microsc. Microanal. 24 (S2) (2018) 310–311, http://dx.doi.org/10. 1017/S1431927618013880.

[11] Du Yingchao, Chen Han, Zhang Hongze, et al. "A very compact inverse Compton scattering gamma-ray source". High Power Laser and Particle Beams, 2022, 34: 104010. doi: 10.11884/HPLPB202234.220132.

[12] S. Stapnes, "Compact Material Analysis for Batteries & Fast Fuel Cell Development", 2022, https://knowledgetransfer.web.cern.ch/kt-fund/projects/compact-material-analysis-batteries-fast-fuel-cell-development.

[13] CHUV Press Release, "CHUV, CERN and THERYQ join forces for a world first in cancer radiotherapy", Lausanne, November 2022.