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XARA: X-BAND ACCELERATOR FOR RESEARCH AND APPLICATIONS

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Abstract

XARA (X-band Accelerator for Research and Applications) is a proposal for a compact ~1 GeV/c accelerator to produce attosecond light pulses in the EUV to soft X-ray region. It is under consideration as a potential future upgrade to the CLARA facility at Daresbury Laboratory, utilising high-performance X-band RF technology to increase the electron beam momentum from 250 MeV/c. Emerging techniques for generating single-cycle undulator light would give access to attosecond timescales, enabling studies of ultra-fast dynamics, while also being very compact. XARA would also enhance the existing capabilities for accelerator science R&D by incorporating X-band development and increasing the electron beam momentum for novel acceleration studies.

INTRODUCTION

We propose a high-energy upgrade of the CLARA facility [1], utilising high-gradient X-band RF technology to achieve a maximum beam momentum of around 1 GeV/c, with FEL light output in the extreme-ultra-violet (EUV) to soft X-ray (SX) regime, including the 'water window' wavelength region between 2.3-4.4 nm. In addition to its inherent scientific interest due to the presence of important K-edges and transparency of water, this wavelength region coincides with state-of-the art technological developments in temporally coherent FEL output [2] and attosecond pulse generation [3, 4].

The aim of the proposal is therefore to deliver a photon source that is attractive to both FEL and HHG users, and to do so through developing advanced accelerator technologies. XARA represents an opportunity to implement the developments in X-band technology and innovative short-period undulators coming from the Horizon 2020-funded project 'CompactLight' [5], of which STFC is a member. STFC is also involved with EuPRAXIA [6] and XARA would be synergistic with EuPRAXIA@SPARC_LAB [7]. Another key feature is the potential to utilise emerging techniques for single-cycle undulator light, as developed by the LUSIA consortium [8]

CLARA is presently supported to phase 2 (250 MeV/c plus full energy beam extraction (FEBE) line and user station). The UK is developing a science case for its XFEL project, due to report in May 2020, which will inform thinking regarding CLARA phase 3 (the FEL line – to demonstrate novel FEL schemes for use in an XFEL [9]). XARA is therefore considered as an alternative or future upgrade option for the straight-ahead line, which would utilise the existing CLARA front-end and building. XARA is currently aiming to fit inside the existing CLARA building footprint, however extension of the building by several tens of meters is feasible, if required.

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SCIENCE CASE

The science case for XARA comprises photon science, particle accelerator R&D and electron beam exploitation.

Photon Science

The science case for XARA is centred on the opportunity to study ultra-fast dynamics [10] in e.g. photosynthesis, photo-induced catalysis and light-wave electronics, and to influence such effects e.g. through coherent control [11]. To do so requires pulse durations on the scale of tens to hundreds of attoseconds. Figure 1 shows the parameter space for relevant existing sources in this area. HHG provides the shortest pulses but with relatively low number of photons per pulse compared to FELs, particularly at higher photon energy. The target for XARA (also shown in Fig. 1) would extend EUV-SX FELs to shorter pulse duration, aiming for higher pulse energies than HHG.

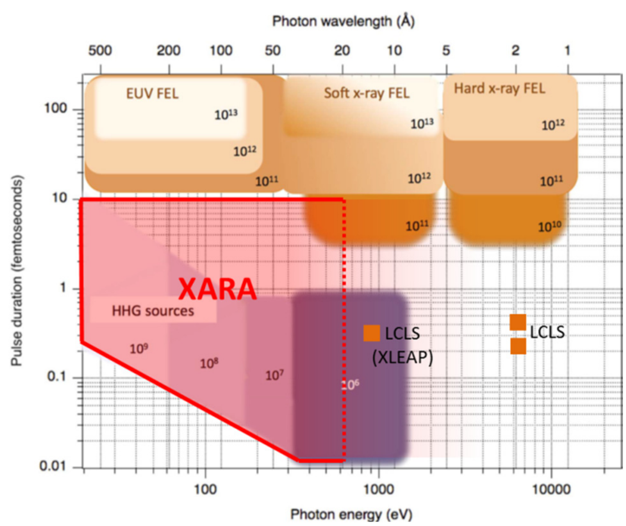

Figure 1: XARA target parameter space relative to the ultrafast science landscape, adapted from [10].

Accelerator R&D/Electron Beam Exploitation

XARA would enhance CLARA's existing function as a centre for accelerator R&D and electron beam exploitation. At present the beam from the CLARA front-end (~35 MeV/c) is used for topics that include novel acceleration, medical applications and basic accelerator R&D [12]. Novel acceleration is a particular focus of the Cockcroft Institute, which is co-located at Daresbury Laboratory (dielectric WFA, PWFA). Medical studies on CLARA include VHEE dose and damage studies, and there are strong links with nearby universities and hospitals. Accelerator R&D includes commissioning of the 400 Hz 1.5

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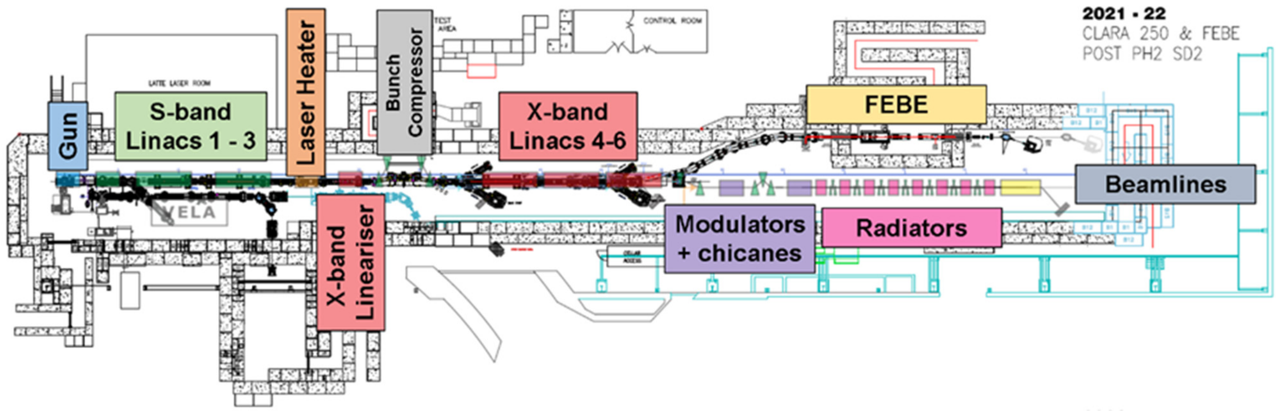

Figure 2: Layout of CLARA phase 2 showing the potential XARA layout overlaid. CLARA linac 4 (S-band) is replaced with 3-4 X-band linacs to achieve ~1 GeV/c beam momentum. The FEL and beamlines section is indicative and could extend beyond the present building if required.

cell RF gun [13, 14], beam studies with superconducting undulators [15, 16], and dielectric de-chirpers [17-19]. Along with cavity BPMs and other diagnostic developments, such as electro-optic bunch length monitors and passive longitudinal streakers, these developments are also relevant for XARA. The present phase of CLARA installation takes the beam to 250 MeV/c with a dedicated experimental user station on the FEBE line (Fig. 2). XARA would increase the momentum for electron beam exploitation in FEBE to ~600 MeV/c, limited by the physical machine layout. New accelerator R&D would focus on X-band linac development and novel undulator light production, whilst providing a new energy regime for existing studies.

ACCELERATOR

This section describes the main components of the XARA accelerator, utilising the CLARA front-end.

S-Band Injector

The CLARA Phase 2 machine (sans linac 4) will act as the S-band injector for XARA. This will provide a ~180 MeV/c, sub-ps FWHM, 250 pC electron bunch, compatible with injection into the X-band linacs. The injector will consist of an S-band 1.5 cell RF photo-injector [13, 14] operating at up to 400 Hz, and up to 120 MV/m in 100 Hz mode, with a dual feed H-coupler to eliminate dipole components in the coaxial input coupler which can lead to transverse beam asymmetry [20], as well as a load-lock in-vacuum cathode exchange system. The front end of CLARA (gun and first linac) has recently been commissioned with a low rep-rate, 2.5 cell, 10 Hz gun, whilst the 1.5 cell cavity will be commissioned in the coming months. The phase 2 machine (incl. linacs 2, 3 and 4, X-band lineariser [21] and variable bunch compressor) will be commissioned in 2021. Significant advances have already been made in both commissioning and experimental running procedures for CLARA, including advances in high level software capabilities [22], such as implementation of a new C++/python API interface to EPICS. This allows for automated accelerator controls, improving reliability and repeatability, such as unmanned cavity conditioning, cavity cresting, BPM calibration, and beam-based alignment, as well as improvements in machine development studies such as fast, reproducible measurements of transverse emittance, longitudinal bunch length and momentum spread. An online model and virtual accelerator have also been implemented [23].

X-Band Linac

The X-band linac section will comprise of 3 or 4 modules similar to those proposed for the CompactLight and EuPRAXIA@SPARC_LAB projects [24], which can be seen in Fig. 3. Each module comprises a high-power RF source of one or two 50 MW X-band klystrons, low loss waveguide and a SLED type pulse compressor, feeding into 4 m of X-band RF cavities. The module will be re-optimised for XARA for two options. The first option is a single bunch, very high gradient option, where the gradient must be greater than 70 MV/m to ensure a beam momentum of 1 GeV/c can be reached with only 3 modules. In this option, because of the limited space for XARA and the relatively low number of modules required, gradient will be prioritised, even at the expense of requiring two klystrons over one. The second option is for a multi-bunch regime, which will require a longer RF pulse or shorter cavities to minimise the filling time (this option is under consideration for drive/witness plasma acceleration or a regenerative amplifier FEL, and would need associated photo-injector upgrades).

Due to the short bunch lengths, short range wake-fields in the X-band cavities have a strong impact on the beam dynamics. If these are found to be deleterious to the beam it may necessitate changes to the X-band cavity design, specifically to widen the iris.

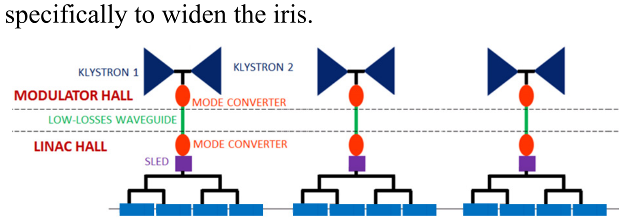

Figure 3: Schematic of the proposed X-band linac section, adapted from [24].

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FEL OPTIONS

CLARA at 250 MeV/c was designed for a shortest wavelength of 100 nm (12.4 eV photon energy). Increasing the beam momentum to 1 GeV/c would provide a factor of 16 reduction to 6 nm (200 eV). Utilising more ambitious undulator technology [5, 15, 16] would allow a significant further reduction, potentially to 2.3 nm (540 eV), covering the 'water-window' region of particular scientific interest (Fig. 4).

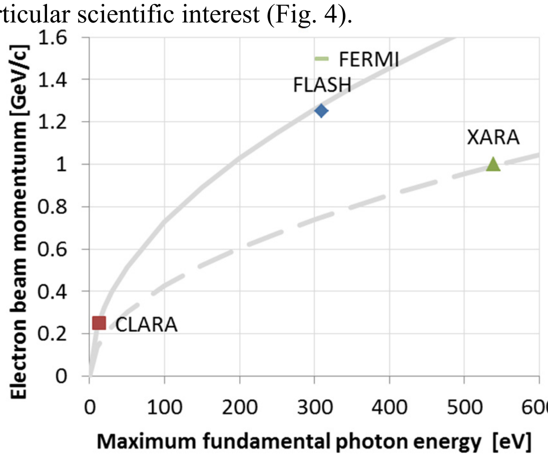

Figure 4: Maximum photon energy at the fundamental against electron beam momentum for relevant facilities. The dashed line indicates the use of advanced short-period undulators to reach higher photon energy compared to presently installed technologies (solid line).

Single-Cycle Undulator Light

A key feature of the XARA proposal is the potential to utilise emerging new FEL techniques for single-cycle undulator light [8]. Application of such methods at XARA wavelengths would deliver attosecond pulses with > 100 nJ pulse energies (Fig. 5), while also being extremely compact (a few metres). There is potential for particular synergy between novel acceleration and light source development, with the former potentially extending the scope of the latter to higher photon energies, and both requiring similar hardware, e.g. high-power lasers.

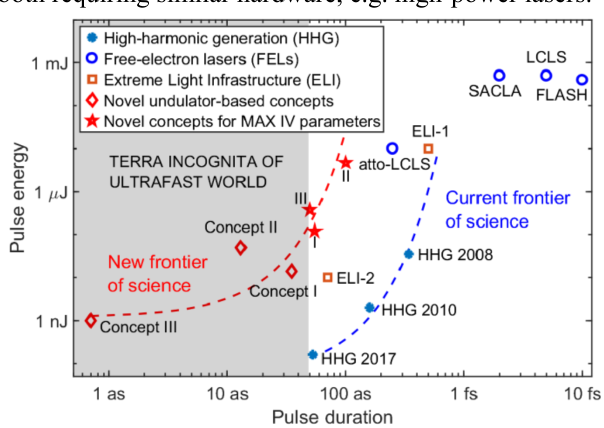

Figure 5: State-of-the-art methods of generating short pulses of light [24], XARA output would be expected to be reasonably close to the red stars, which were modelled at 1.5 GeV/c.

SASE and Seeding

A longer undulator (~15 m) would allow access to a larger parameter space, including longer pulses with significantly higher pulse energy (>100 μJ). Figure 6 shows SASE simulation results. Seeding and associated advanced FEL schemes [2] could also be implemented.

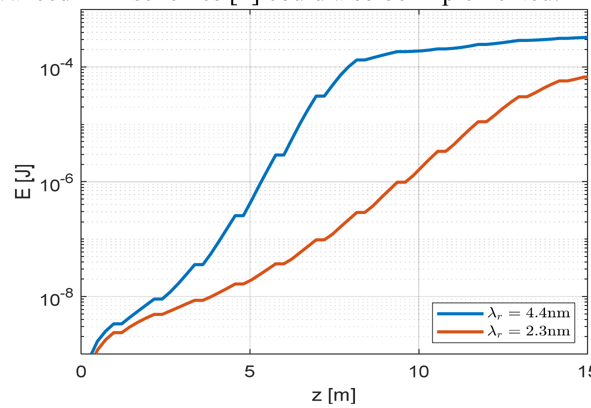

Figure 6: Simulated FEL pulse energy vs distance along the undulator for XARA at water-window wavelengths.

START-TO-END SIMULATIONS

Start-to-End (S2E) simulations of XARA with best-guess models of X-band linac structures and associated wakefields have been performed using a python-based framework, integrated with the Genesis FEL code. A full MOGA optimisation was undertaken to ascertain feasible FEL light properties and is more fully described in [25]. Initial results are encouraging: Figure 7 shows the Pareto front after optimising on maximising pulse energy and minimising bandwidth for a XARA simulation utilising ASTRA, Elegant and Genesis with 32k macro-particles.

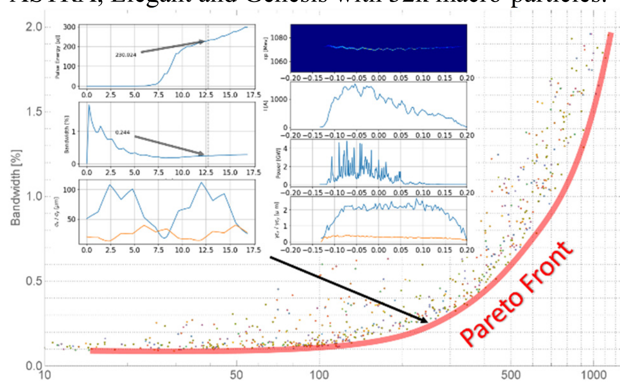

Figure 7: Pareto front in Pulse energy – Bandwidth space for a S2E model of XARA, using Genesis in SASE mode. A 230μJ representative point on the Pareto front is shown.

SUMMARY AND NEXT STEPS

XARA would be a medium-scale national light-source facility and a centre for particle accelerator R&D, using existing infrastructure to significantly reduce cost. The next steps are to consult the UK user base to determine the benefits of short pulses vs higher pulse energy; optimise the RF module design; and investigate wake-fields, compact optical beamlines and detailed FEL designs.

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