THE VELA AND CLARA TEST FACILITIES AT DARESBURY LABORATORY

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on behalf of the VELA and CLARA development teams.
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Abstract

The Versatile Electron Linear Accelerator (VELA) provides enabling infrastructures targeted at the development and testing of novel and compact accelerator technologies, specifically through partnership with academia and industry, aimed at addressing applications in medicine, health, security, energy and industrial processing. The facility is now fully commissioned and is taking advantage of the variable electron beam parameters to demonstrate new techniques/processes or otherwise develop new technologies for future commercial realization. Examples of facility exploitation include; electron diffraction and new cargo scanning processes. The Compact Linear Accelerator for Research and Applications (CLARA) will be a novel FEL test facility, focused on the generation of ultra-short photon pulses with extreme levels of stability and synchronisation. The principal aim is to experimentally demonstrate that sub-cooperation length pulse generation with FELs is viable, and to compare the various schemes being championed. The results will translate directly to existing and future X-ray FELs, enabling attosecond pulse generation. The VELA and CLARA facilities are co-located at Daresbury Laboratory and provide the UK with a unique platform for scientific and commercial R&D using ultra-short pulse, high precision electron and photon beams.

VELA AND CLARA ACCELERATORS

VELA is a high performance, modular injector facility capable of delivering stable, high quality and customisable electron beams into two dedicated, shielded test enclosures (BA1 and BA2) for the development and qualification of advanced accelerator systems [1] (see Fig. 1).

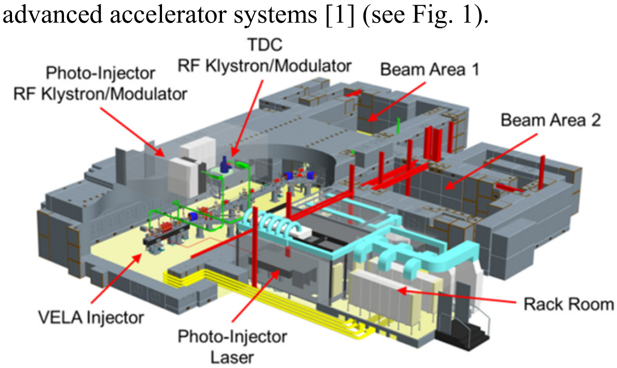

Figure 1: VELA accelerator layout.

CLARA is a dedicated FEL test facility [2] currently under construction, capable of testing new FEL schemes that have the capability to enhance the performance of short wavelength FELs worldwide (see Fig. 2). The primary focus of CLARA is for ultra-short pulse generation, stability and synchronisation. Enhancements in these three areas will have a significant impact on the experimental capabilities of FELs in the future. The wavelength range chosen for the CLARA FEL is 100 – 400 nm, appropriate for the demonstration of advanced FEL concepts on a relatively low energy accelerator.

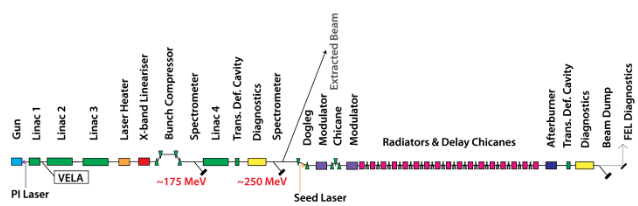

Figure 2: CLARA Design Schematic.

VELA Commissioning and Characterisation

Since achieving first electron beam in early 2013 [3], a number of commissioning and beam characterisation experiments have been completed. VELA has a suite of diagnostics in a specially designed beamline consisting of quadrupoles, YAG screens, BPMs, wall current monitor, Transverse Deflecting Cavity (TDC) and a spectrometer line for 6D beam characterisation (see Fig. 3), which have been used to characterise the RF gun performance and beam transverse and longitudinal phase space.

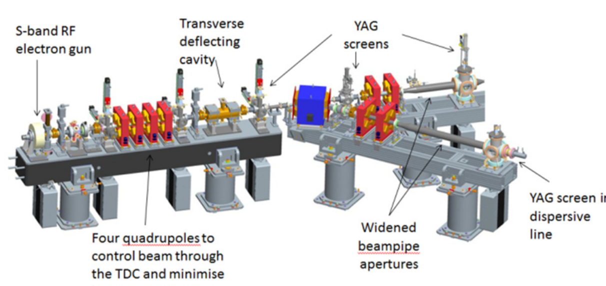

Figure 3: VELA beam diagnostics beamline.

Bunch charges over the range 40 fC (for electron diffraction) to 250 pC with a peak beam energy of ~5 MeV reliably achieved, with 8 MW of RF power in the S-Band RF gun cavity [4]. Dark current, measured throughout commissioning and operation with two different cathodes, has shown continual improvement, decreasing from 1.2 nC to 130 pC per 3 μs RF pulse at a gradient of 70 MV/m. The longitudinal and transverse qualities of the beam have been characterised through, slit and quadrupole scans, spectrometer line and TDC measurements. This is the first utilisation of a new simultaneous quadrupole scanning technique [5, 6], demonstrating (measured at different locations in the VELA line): micron-scale transverse emittance at 4.5 MeV and low charge of 10 pC, with some spurious horizontal-vertical coupling at the 1:2 level and rms bunch lengths of 2.5 ps at 100 pC with a momentum spread of 0.25 % (see Fig. 4).

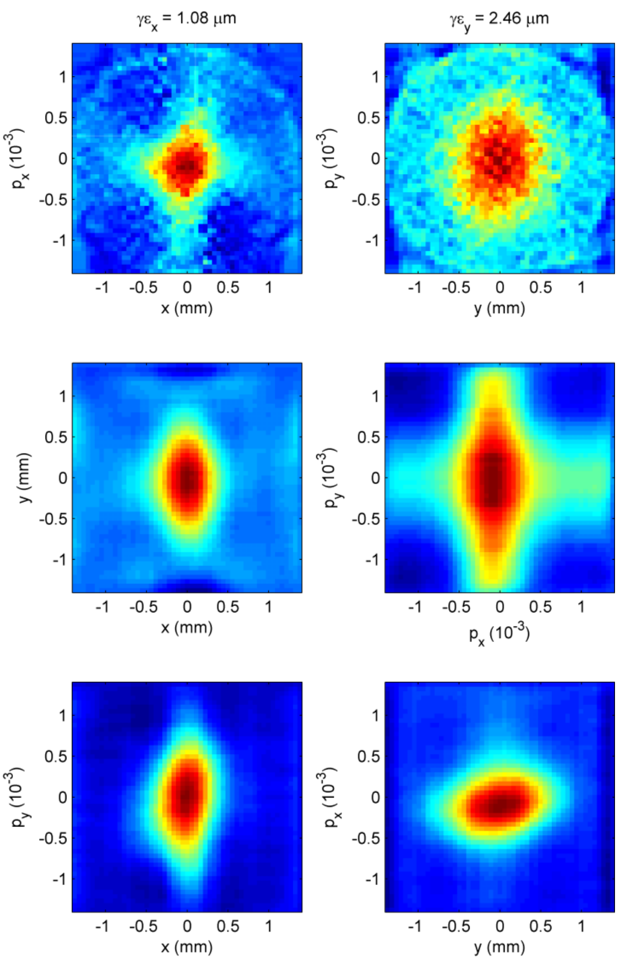

Figure 4: Tomograms of the beam distribution in the 4D transverse phase space and rms emittance values.

Electron Diffraction

Accelerator based electron diffraction enables ultrafast structural analysis of materials. The making and breaking of chemical bonds occurs on the timescale of a molecular vibration, i.e. 10s of femtoseconds (fs). By operating at a few MeV it is possible to minimise space charge limitations to obtain such short bunches with sufficient charge, to enable high quality diffraction data to be obtained in a single shot. The technique therefore entirely complements structural dynamics and fs crystallography with X-ray FELs, with the following advantages:

1. Much higher scattering cross sections for electrons than X-rays (> 10^4) - smaller samples needed,
2. Lower energy transfer per inelastic scattering event - less sample damage,
3. Smaller and cheaper multi-MeV accelerators, opposed to multi-GeV accelerators for X-ray FELs.

The electron diffraction system installed on VELA is described elsewhere [7], the accelerator layout is shown in Fig. 5.

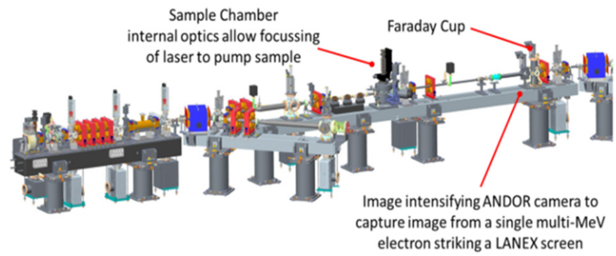

Figure 5: VELA electron diffraction system.

It consists of a diffraction chamber 8.5 m from the gun which holds a sample carousel, shaping apertures and screen for viewing the beam, and a detection system consisting of a screen at 11.9 m from the gun viewed with an ANDOR camera, capable of single photon detection. A Faraday cup can be inserted into the beam just in front of the detection screen. The system has allowed single shot diffraction patterns to be obtained with sub-pC bunches from a variety of simple metals and semiconductors [8], as shown in Fig. 6.

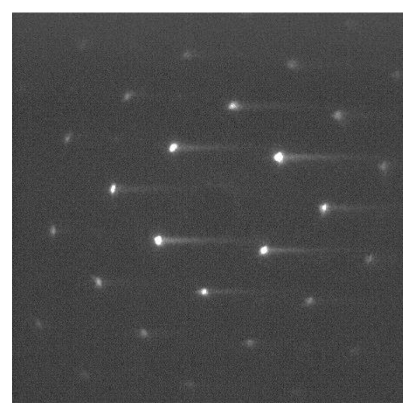

Figure 6: Diffraction pattern from single gold crystal obtained with a single 40 fC electron bunch.

Cargo Scanning Time of Flight

The VELA facility has also enabled industry to conduct development of novel technologies for societal applications. For example, STFC are working in close partnership with Rapiscan Systems and University College London to develop time-of-flight Compton scatter imaging (ToF CSI) with the goal of producing commercial systems for enhanced cargo scanning in aviation and commercial shipping markets [9].

The nominal beam energy of the VELA source allows examination at a suitable penetration depth in diverse materials, whilst the repeatable picosecond pulse structure and advanced timing diagnostics allow accurate time of

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flight information in order to reconstruct 3-D images of cargo components.

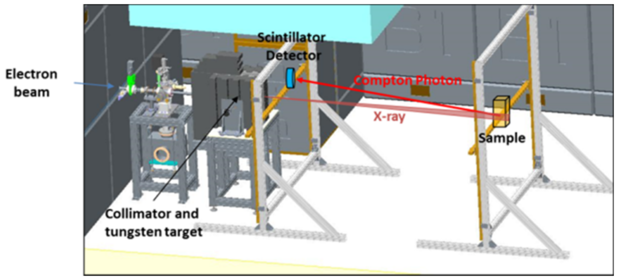


Figure 7: ToF CSI experimental layout on VELA.

The technique utilises the relationship between the Compton scatter interaction and the photoelectric interaction, to facilitate basic material determination. The experimental set-up utilises a rotating collimator with integrated tungsten target to generate a pencil beam of high-energy X-rays (see Fig. 7). Using a 10 Hz, 4.5 MeV electron beam with an average bunch charge 100 pC incident on a tungsten target in VELA BA1, it was possible to undertake proof-of-concept experiments to successfully differentiate between high density polyethylene test objects mounted at varying positions along the beam axis using a single $CeBr_3$ scintillator detector, as illustrated in Fig. 8.

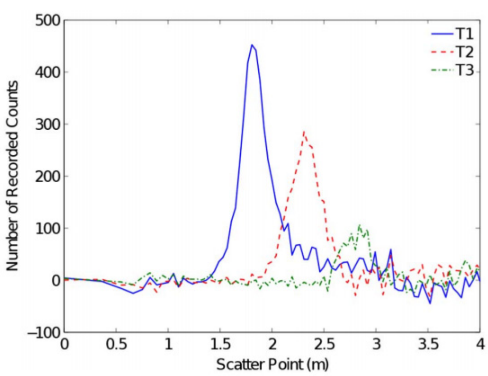


Figure 8: Scatter histogram for detector, with test objects at 1.8 m (T1), 2.3 m (T2), and 2.8 m (T3).

A subsequent experimental programme, exploiting the reduced background levels available off-axis in VELA BA2, has simplified data reduction and facilitated comparison of multiple scintillator detector arrays at varying angles of incidence and resolution as a further development step to generating comprehensive 3-D images of the samples under test, results for which are awaiting publication.

User Area Capabilities

A new multi-user facility located in BA1 (see Fig. 9) has recently been commissioned using ~4 MeV beams from the 10 Hz VELA RF gun [4]. The BA1 beamline is currently being upgraded to allow experiments at ~50 MeV energies that will be available after commissioning of the CLARA Front End (CLARA-FE). The main feature of the beamline is a 2 m long, experimental vacuum chamber with easy access for installation, modification and change-over between different experiments. Quadrupole triplets upstream and downstream of this chamber allow flexible manipulation of the beam properties for interaction within the chamber and for beam imaging in the downstream energy spectrometer.

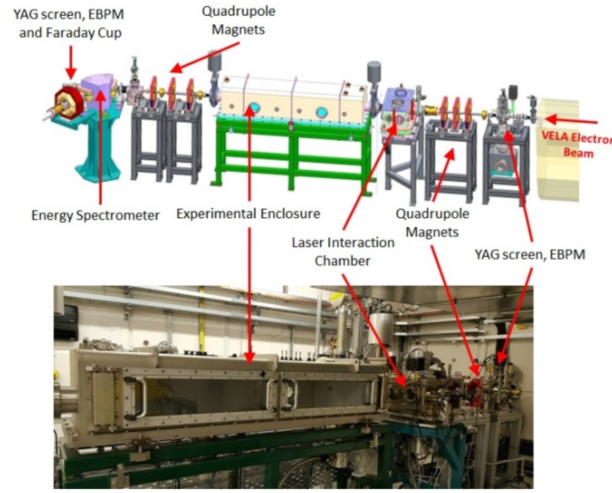


Figure 9: New VELA UA1 beamline configuration.

Electron bunches of up to 250 pC can be delivered to BA1 either from the High Repetition Rate Gun (HRRG) (~4 MeV beam energy and several ps long bunches at up to 400 Hz) or from the 10 Hz gun (~50 MeV beam energy at up to 10 Hz) located on CLARA-FE. In the latter case, bunches up to 50 MeV can be compressed longitudinally in the dog-leg linking CLARA and VELA, see Fig. 10, to sub-ps levels. Simulations at ~50 MeV beam energy predicts bunch lengths down to 300 fs RMS and transverse beam sizes of <100 μm RMS at the BA1 interaction point.

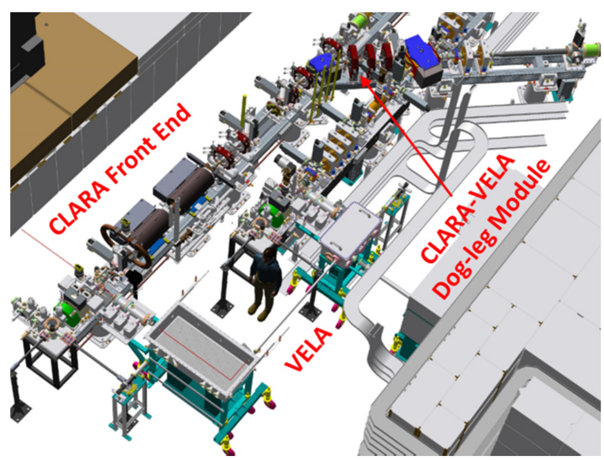


Figure 10: CLARA-FE and VELA interfacing.

A high power 802 nm laser beam of 16 TW peak power, 50 fs pulse duration, 0.8 J pulse energy (after compressor) and 10 Hz pulse repetition rate can also be delivered to the large chamber in BA1. Laser beam optics allow focusing of the beam to ~30 μm transverse beam size thus enabling ~ 1.018 kW/cm^2 peak power density at the BA1 interaction point. This powerful laser beam can be used for a variety of laser driven acceleration experiments either on its own (like LWFA) or in combination with electron beams.

CLARA DESIGN

The VELA 10 Hz RF photo-gun will be initially operated on the CLARA beamline. Following beam characterisation of the 400 Hz High Repetition Rate Gun (HRRG) on the VELA beamline, it will be swapped with the 10 Hz gun. As shown in Fig. 2, immediately following the CLARA gun is Linac1 and together with its solenoids, it will be operated to provide correct emittance compensation and acceleration in one of two modes; Booster, where the beam energy on exit will be up to 50 MeV; and Buncher, where full longitudinal compression is achieved in this section at the cost of energy reduction to ~15 MeV. After Linac1 is a section incorporating an insertable variable aperture collimator and matching quadrupoles feeding into a dual purpose spectrometer and short transfer dogleg to the VELA beamline. This enables experiments on VELA to be conducted using either standard or high repetition rate guns. Linac2 and Linac3 follow this spectrometer and beam energies of 105 MeV and 180 MeV will be reached at this point, depending on the operating mode. A laser heater section with associated matching whilst not fundamentally required to obtain lasing on CLARA, will facilitate studies in support of a future UK-XFEL [10]. A fourth-harmonic (11.992 GHz) cavity is then utilised to linearise the longitudinal phase space. A continuously variable deflection bunch compressor succeeds this, providing R_{56} up to -72 mm.

Table 1: CLARA Beam Operating Modes

Parameter	Unit	Beam Mode			
		Short	Long	U.Sh.	Flat
Energy	MeV	240 150	150 240	240	240
Δt_{FWHM}	fs	585	1875	40	250
Charge	pC	250	250	20	250
Slice	fs	25	25	5	15
I_{peak}	A	400	125	1000	400
ε_N target	µm	0.5	0.5	1.0	0.5
ε_N max	µm	1.0	0.8	1.5	1.0
σ_δ target	keV	25	25	100	25
σ_δ max	keV	120	75	150	100
E. Chirp	MeV/ps	n/a	n/a	n/a	< 1
E. Var.	keV	n/a	n/a	n/a	< 240

It is intended that a full range of bunch compression schemes from full velocity bunching to full magnetic compression will be studied on CLARA. A short diagnostics and spectrometer line precedes Linac4 where a final energy of 250 MeV is reached. A dedicated bunch diagnostics section incorporating transverse deflecting cavity (TDC), phase advance and spectrometer is specified to resolve features of 10 fs duration in the bunch longitudinal phase space. The FEL section consists of two modulator undulators (of 0.9 m and 1.1 m respectively) separated by a phase space mixing chicane, with 17 x 0.74 m radiator undulators separated by delay chicanes.

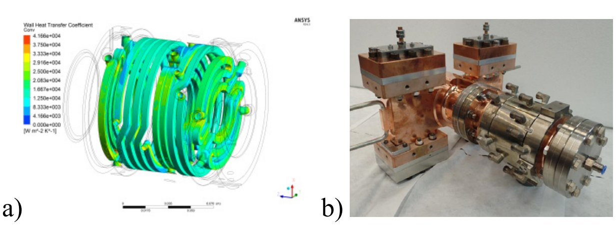
The final section is a second TDC diagnostics section identical to that prior to the FEL, which will enable lasing features to be identified in the bunch. Comprehensive start-to-end simulations have been performed for the various operating modes using ASTRA, CSRTrack and GPT [11]. Collective effects such as space charge, geometric and coherent radiation wakefields are included. These various modes are shown in Table 1.

CLARA High Repetition Rate Gun

The HRRG photo-injector for CLARA was developed in collaboration with Institute for Nuclear Research RAS, Moscow and Lancaster University. For delivering high brightness beams for CLARA FEL experiments, the cathode field required is 120 MV/m at a repetition rate of 100 Hz. This constraint is lowered somewhat for the 400 Hz mode to 100 MV/m for VELA operation. The photo-injector must therefore have high power handling capabilities of up to 5.6 kW. The final design is based on a 1.5 cell normal conducting S-band RF cavity [12]. It has a coaxial coupler with dual feed RF input with phase adjustment of each feed to supresses any dipole component in the coaxial coupler line.

The electrons are produced from interchangeable metal photocathodes illuminated with an UV laser. The photocathode plug design and transport system is compatible with the ones used at DESY/LBNL/FNAL and allows for testing different types of photocathodes. The on-site photocathode preparation and characterisation facility is now under commissioning. Beam focusing is provided with 0.4 T main solenoid and a bucking coil.

Operation of the CLARA seeded FEL requires a very stable beam arrival time at the point of interaction between the seeding laser and electron beam with rms jitter of less than 64 fs. To achieve this, the RF amplitude stability must be 0.1 % rms and the phase stability 0.1 ° rms, necessitating a temperature stability of 0.009 °C rms [2, 13]. The RF cavity has a probe port in the second cell for feed-forward amplitude correction and a robust thermo-stabilisation system of water channels built into the copper cavity structure (see Fig. 11a), fed by an advanced high resolution control system.



a) b)

Figure 11: a) Cavity cooling channel pressure variation and b) the delivered 400 Hz photo-injector cavity.

The cavity was manufactured at Research Instruments GmbH (see Fig. 11b). A sophisticated tuning procedure was developed to tune the field flatness and frequency before brazing. Low-power tests confirmed the cavity resonant frequency of 2.9985 GHz at 48°C operating temperature and a field flatness of 98 ± 1% [14]. The surface finish was carefully specified in order to achieve a

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high quality factor Q_0 of 13350 ± 280 with Mo cathode plugs. This increases further to 14230 ± 120 using a Cu cathode plug. The cavity is overcoupled a small amount with a coupling coefficient β equalling 1.05 ± 0.017.

FEL Research Priorities

The schematic layout of the FEL section (excluding diagnostics) is shown in Fig. 12. The FEL research priorities are categorised into two general classes. The ‘early stage’ topics require no synchronisation between the electron bunch and external lasers and are those that are easier to implement. However all these early topics are potential candidates for operating modes of a future UK X-FEL so the experience and data obtained will be invaluable. These ‘early stage’ topics are as follows:

- Single spike SASE [15] – CLARA will be operated in Ultrashort mode. The bunch will be short enough to generate a single coherent SASE spike.
- Two-colour operation [16] – the undulator modules can be set to be resonant at one of two wavelengths so that the FEL lases at these two wavelengths simultaneously.
- Tapering [17] – at longer wavelengths the FEL will saturate approximately half-way along the undulator. The remaining undulator sections will be tapered (by gradually reducing their field strength) to maintain resonance between the FEL radiation and the electron bunch, thereby greatly increasing output.

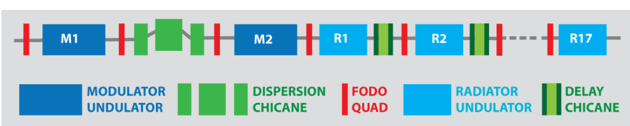

Figure 12: FEL Section magnetic layout schematic.

The major research topics are those for which CLARA can have the greatest impact in experimentally validating novel FEL schemes, such topics are as follows:

- <u>Mode-Locking</u> [18] – this scheme uses the electron beam delay chicanes between the undulator modules. It also requires interaction with a long wavelength (30 - 50µm) laser in a modulator undulator to induce an energy modulation along the bunch. Simulations predict FEL pulses comprising trains of phase-locked spikes each of duration around 15 optical cycles, significantly shorter than the FEL cooperation length.
- <u>High-Brightness SASE (HB-SASE)</u> [19] – the magnetic chicanes along the undulator lattice are used to increase the slippage and reduce the SASE FEL bandwidth by an order of magnitude. The scheme is an alternative to self-seeding - because it uses no optics it may prove to be more easily tunable over wide wavelength ranges and be more appropriate for high-repetition rate FELs.
- <u>Mode-Locked Afterburner</u> [20] – an afterburner undulator installed after the FEL radiator will produce a train of phase-locked spikes of FWHM duration around 5 optical cycles – at 100nm wavelength this corresponds to sub-fs rms pulses.

Future Plans for VELA and CLARA

The installation of CLARA-FE is expected to be complete by early Jan’17. Its beam commissioning will commence immediately after completing the technical system checks. After establishing the beam transport from CLARA-FE, through the CLARA to VELA dogleg to the energy spectrometer and to VELA BA1 and BA2, a programme of beam stability measurement and beam characterisation will be undertaken. When ready, the commissioning and characterisation of the HRRG on the VELA line will commence.

With commissioning of both beam lines, it will be possible to send either low energy (4 - 5 MeV) beam from HRRG (up to 400 Hz repetition rate) and a high energy (~50 MeV) beam (10 Hz repetition rate) from CLARA-FE to VELA beam line and beam areas (maximum energy to BA2 is restricted to 25 MeV due to operating magnet parameters). It is expected that once a satisfactory beam transport is established, the upgraded BA1 user-facility beamline will be commissioned allowing setting up first beam exploitation experiments. The programme of beam characterisation and R&D to establish the design parameters for CLARA will continue alongside some dedicated allocation time for exploitation programme. It is anticipated that swapping the RF guns will be possible in early 2018, giving enough time to characterise HRRG with different cathodes. With the HRRG gun installed on the CLARA-FE, it will then be possible to meet CLARA specifications of 100 Hz repetition rate and at the same time provide higher beam power to the VELA beam areas.

It is expected that by end of 2018, CLARA phase 2 modules (prepared elsewhere on-site) will be ready to be moved to the accelerator tunnel with commissioning to start in late 2019. CLARA as proposed should allow demonstration of first lasing by end of 2021. The commissioning and exploitation programmes will be then managed to maximise the benefits to future UK X-FEL, accelerator R&D in novel concepts and benefit to the industry.

ACKNOWLEDGEMENTS

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