THE DESIGN OF THE FULL ENERGY BEAM EXPLOITATION (FEBE) BEAMLINE ON CLARA

D. Angal-Kalinin, A. R. Bainbridge, J. K. Jones, T. H. Pacey, Y. M. Saveliev, E. W. Snedden
ASTeC, STFC Daresbury Laboratory, UK

Abstract

The CLARA facility at Daresbury Laboratory was originally designed for the study of novel FEL physics utilising high-quality electron bunches at up to 250 MeV/c. To maximise the exploitation of the accelerator complex, a dedicated full energy beam exploitation (FEBE) beamline has been designed and is currently being installed in a separate vault on the CLARA accelerator. FEBE will allow the use of high charge (up to 250 pC), moderate energy (up to 250 MeV), electron bunches for a wide variety of accelerator applications critical to ongoing accelerator development in the UK and international communities. The facility consists of a shielded enclosure, accessible during beam running in CLARA, with two very large experimental chambers compatible with a wide range of experimental proposals. High-power laser beams (up to 100 TW) will be available for electron-beam interactions in the first chamber, and there are concrete plans for a wide variety of advanced diagnostics (including a high-field permanent magnet spectrometer and dielectric longitudinal streaker), essential for multiple experimental paradigms, in the second chamber. FEBE will be commissioned in 2024.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) is an ultra-bright electron beam test facility being developed at STFC Daresbury Laboratory. CLARA has been designed to test advanced Free Electron Laser (FEL) schemes that could be later implemented on existing and future short wavelength FELs, such as a UK XFEL.

CLARA is being constructed in stages: Phase 1 was completed in 2018 and consisted of the CLARA Front End: electron bunch production at 50 MeV, 100 pC at 10 Hz. Bunch charge up to 250 pC was achieved from the upgraded gun at 10 Hz with a hybrid Cu-photocathode. Design and commissioning of the CLARA Front End is detailed in Reference [1]. Phase 2 is currently under construction, and elevates the beam to 250 MeV/c, 250 pC at 100 Hz. A novel 100 Hz photo-injector gun [2] is currently being commissioned on the Versatile Electron Linear Accelerator (VELA)[3], situated adjacent to CLARA, and will be swapped over to the CLARA line when fully characterised. Phase 3 will allow installation of an FEL, seeding laser and modulators along with associated photon diagnostics. Phase 3 of CLARA is not yet funded.

During the construction of CLARA, in Phases 1 and 2, access to electron beams at ~35 MeV/c was made available to users from academia and industry. This enabled the testing of novel concepts and ideas in a wide range of disciplines, including development of advanced accelerator technology, beam diagnostics, medical applications and novel particle beam acceleration and deflection concepts [4]. Based on increasing user demand for access to the CLARA high brightness electron beam, a decision was made to design and build a dedicated beamline for user applications at the full CLARA beam momentum of 250 MeV/c.

The FEBE beamline is being built to transport 250 MeV/c beam to a dedicated hutch area, containing two experimental chambers, for user access. As a key component of the design, the hutch will be accessible without switching off the accelerator, allowing users to set up and access their experiments as required. The total beam power within the hutch is limited to ~6 W, which offers sufficient flexibility with available bunch charge (maximum 250 pC), bunch repetition rate (maximum 100 Hz) and beam momentum (up to 250 MeV/c).

The interaction of high-quality electron bunches with high instantaneous power laser light (>100 TW) is foreseen as a key component of the FEBE beamline exploitation, and will enable research in novel acceleration areas including LWFA, PWFA and dielectric laser acceleration (DLA). Beams accelerated inside the hutch can be accommodated up to 2 GeV/c.

FEBE DESIGN

The top-level overview of the CLARA and FEBE beamlines is shown in Fig. 1. The FEBE experiment hutch is a large (10x5.4x3m^3), shielded, and versatile area for performing electron beam exploitation experiments. Within the hutch, the beam transport is designed to deliver a strong focusing interaction point (IP) at two locations. Each IP is located within a large-volume (~2 m^3) vacuum experiment chamber.

A double-IP design is used to enable flexibility in experimental design and implementation, with most experiments having experimental apparatus situated in the first FEBE experimental chamber (FEC1) and diagnostics and other monitoring equipment situated in the second chamber (FEC2). A high power laser co-propagates with the electron beam to a common focus (IP1) in FEC1, with this capability included through a dedicated laser mirror box chamber (FMBOX1) upstream of the first experiment chamber, and a second mirror box (FMBOX2) between chambers to extract the laser following interaction.

The experimental hutch is connected to the main CLARA accelerator using a series of FODO arc cell structures optimised for minimal CSR emittance growth. The FEBE transverse offset is achieved using four 14° dipoles, which enables both sufficient space for an FEL seeding chicane, and fits within the existing CLARA shielding.

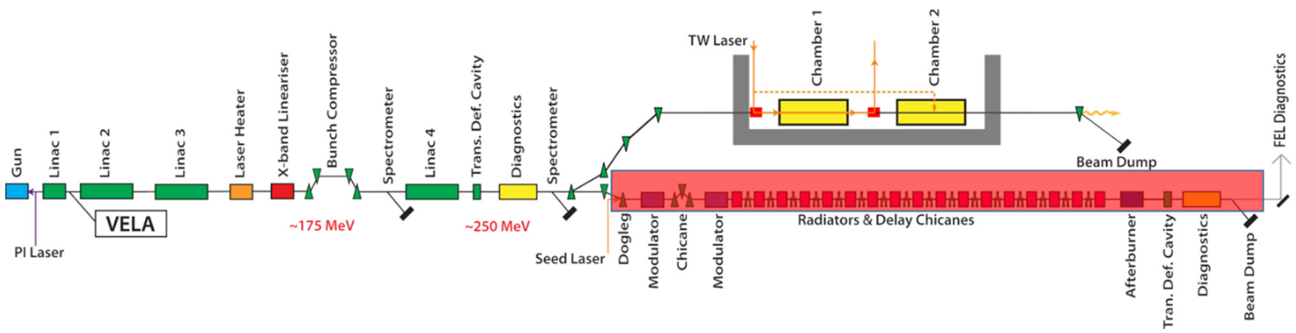

Figure 1: Overview of the CLARA and FEBE beamlines. The proposed CLARA FEL location is highlighted in red.

This solution leads to a strong focusing, non-isochronous arc with large natural 2nd-order longitudinal dispersion, requiring correction by sextupoles located at points of high dispersion. A post-hutch transport line is designed to provide transport to the beam dump, whilst also providing energy spectrometry of the electron beam(s). A 20° dipole magnet is used to bend the beam through to a large aperture YAG for beam imaging. The nominal beam momentum for the FEBE experimental hutch is 250 MeV/c. However, it is envisaged that some experiments, such as novel acceleration techniques, may produce beams of higher momenta. To allow for the possibility of transporting such beams, all of the post-FEC1 IP magnets are specified for beam momenta up to 600 MeV/c which allows for high energy beam transport to the spectrometer and momentum measurements using the dump YAG station. Higher energy beam spectrometry measurements (up to 2 GeV/c) are also possible in FEC2 using a dedicated PM spectrometer. Bunch properties at the FEC1 IP are expected to achieve >4 kA peak current with transverse spot-sizes of ~20 µm or less at 250 pC. Standard beam operation modes for different experiment classes are currently being refined, and for some modes additional permanent-magnet quadrupoles may be installed in-chamber for plasma-cell matching etc.

FEBE DIAGNOSTICS

FEBE Arc

The arc is instrumented using two BPMs and one YAG station per cell. The YAG station is placed at a location of roughly symmetric transverse beta-function, simplifying commissioning set-up. The BPMs are located directly before each YAG for cross-calibration, with a second BPM located just prior to the dipole. One YAG station, at a point of high dispersion, also includes a mask array, for shaping of the bunch longitudinal distribution. Layout of the shaping mask array is shown in Fig. 2, enabling generation of a variety of longitudinal bunch distributions:

- Drive/main bunch-pairs with variable delay,
- A single ultra-short (~fs), low charge, bunch,
- A drive bunch with a train of witness bunches.

A beam arrival monitor (BAM) is located in the pre-hutch beamline for electron-laser timing synchronisation and monitoring. A coherent transition radiation-based longitudinal diagnostic for relative bunch length measurement is also included before the hutch. Each of the arc dipoles includes ports for extraction of CSR. An integrated current transformer is located in the final straight for bunch charge measurement before the experimental hutch.

The CTR-based diagnostic will provide an online bunch compression monitor (BCM) by simply collecting and measuring the CTR pulse energy with a pyroelectric detector; it can be extended later to include spectral characterisation and bunch length estimation. Both a solid disc CTR target and a target with a small clear aperture in the centre will allow for non-destructive online monitoring using coherent diffraction radiation (CDR).

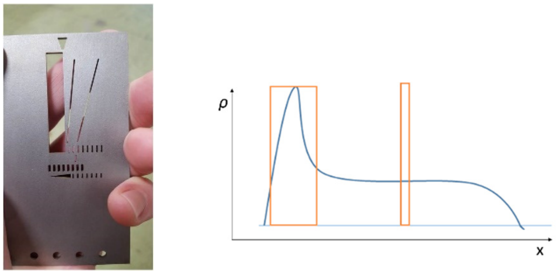

Figure 2: Mask design (left) and desired energy spectrum of the electron bunch at the position of the mask to generate drive-/main-bunch pairs (right).

FEC2 Diagnostics

The design of FEC2 provides a great degree of flexibility allowing addition or removal of specific diagnostic components and re-positioning of translation stages. A generic experimental diagnostic station in FEC2 is shown schematically in Fig. 3, and consists of:

1. A bespoke broadband dielectric wakefield streaker for measuring a wide range of bunch lengths including ultra-short (<10fs)
2. Multiple translation stages and YAG screens for measurement of beam optics
3. Additional space for installation of horizontal and vertical slits for emittance measurements and electro-optic components

Following the FEBE hutch there is an OTR station for high resolution imaging and beam emittance measurement [5].

Spectrometer Dipole

For broadband momentum spectrometry a purpose-built PM dipole can be used in FEC2, as shown in Fig. 4.

The spectrometer dipole design mimics a traditional C-core dipole magnet allowing all beam energies to be imaged simultaneously. The flux is provided by a series of

NdFeB blocks with a Ni-Cu-Ni coating to ensure vacuum compatibility. The magnet design gap of 20mm is chosen as a compromise between flux and potential beam damage from highly divergent electron bunches.

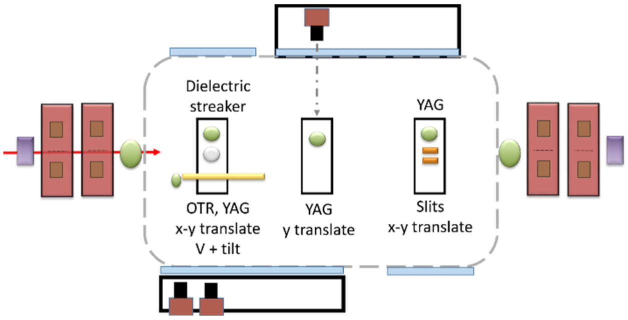

Figure 3: Proposed experimental diagnostic layout in FEC2.

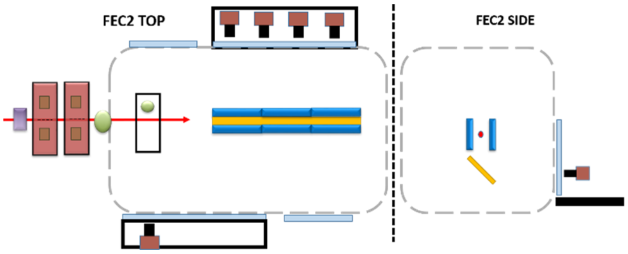

Figure 4: Spectrometer with screen and cameras for wide-energy spectrometry in FEC2.

Finite element modelling in OPERA has been performed in both 2D and 3D, achieving a uniform field of 0.72 T, which is sufficient to achieve good performance over the ~100-2000 MeV/c momentum range. The magnet, shown in Fig. 5, is modular in design, being split lengthwise into up to 6 identical sections, slotted together with a series of precision metal dowels, and allowing an alignment repeatability of ~10 um.

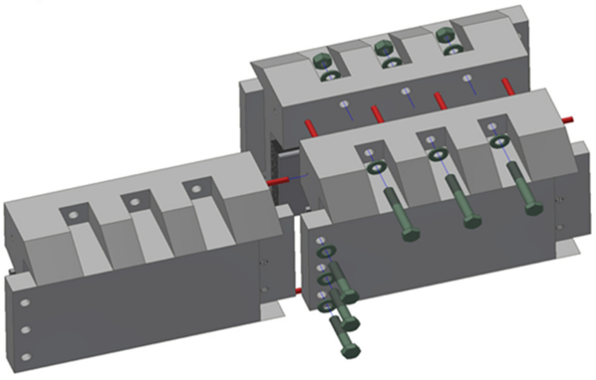

Figure 5: Modular permanent magnet spectrometer design with precision metal dowels.

LASER SYSTEM

The FEBE project includes funding for a ~100 TW Ti:Sapphire laser system. The laser transport system inside the FEBE hutch is shown in Fig. 6 and facilitates two primary classes of experiment: laser light propagates collinear with the electron beam to a common focus in FEC1 (for e.g., plasma wakefield acceleration, generating a plasma channel or driving a plasma wake); the laser is delivered directly to FEC1 without prior manipulation, and prepared electron interaction in the chamber (for e.g., THz acceleration and laser-driven particle beam diagnostics).

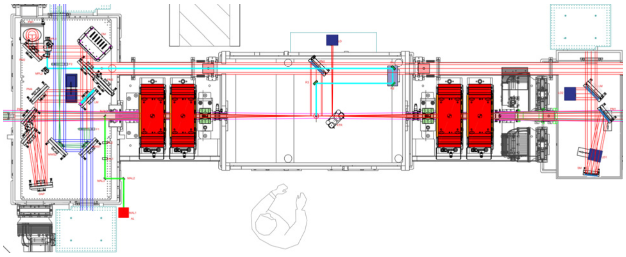

Figure 6: Laser transport schematic in the FEBE hutch.

Laser focussing is achieved using an off-axis parabola (OAP) in FMBOX1, along with adaptive optics components (deformable mirror, DM, and wavefront sensor, WS). A motorized mirror within FMBOX1 can be used to bypass the OAP and deliver laser light to FEC1 via a connecting vacuum pipe.

Leakage through one of the transport mirrors is used to seed online diagnostics, including the WS, which must be placed at a conjugate plane to the DM. A separate in-air diagnostics line includes diagnostics for pulse energy, spectrum, and duration.

Following IP1 the laser expands before being separated from the electron beam using a holed mirror in FMBOX2. The laser transport is symmetric about IP1 (in FEC1) and allows the return beam to either be dumped in FMBOX2 or transported to a second in-air diagnostics platform. Longer-term use of FEBE may support delivery of laser light to FEC2, to maximise use of the available area and potentially facilitate two-pulse experiments: for example, characterisation of novel accelerated beams using laser-driven diagnostics.

CONCLUSIONS

Construction of the FEBE beamline, transporting a 250 MeV/c CLARA beam to a dedicated experimental hutch, is under way at Daresbury Laboratory. The FEBE arc allows for a separate shielded hutch, whilst retaining space for a future CLARA FEL. In addition to flexibility in the upstream beamline (velocity bunching, variable bunch compressor), the FEBE arc can be used for longitudinal manipulation of CLARA bunches through beam masking. The FEBE hutch incorporates two large experimental chambers and transport for ~100 TW laser for laser-electron beam interactions in the first chamber, enabling a suite of novel acceleration experiments. The second chamber incorporates novel diagnostics, such as dielectric streakers, to fully characterise post experiment beams.

ACKNOWLEDGEMENTS

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