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DEVELOPMENT OF A 6D ELECTRON BEAM DIAGNOSTICS SUITE FOR NOVEL ACCELERATION EXPERIMENTS AT FEBE ON CLARA

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Abstract

The FEBE beamline at the CLARA facility will combine a 250 MeV FEL quality electron beam with a 100 TW class laser. One area of research FEBE will support is novel acceleration schemes; both structure and plasma based. There are stringent diagnostic requirements for measuring the input electron beam and challenges in characterisation of the accelerated beams produced by these novel schemes. Several of these challenges include measurement of: micrometer scale transverse profiles, 10 fs scale bunch lengths, single shot emittance, broadband energy spectra at high resolution, and laser-electron time of arrival jitter. Furthermore, novel shot-by-shot non-invasive diagnostics are required for machine learning driven optimisation and feedback systems. This paper presents an overview of R&D activities in support of developing a 6D diagnostics suite to meet these challenges.

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. CLARA is being constructed in phases. Phase 1 was commissioned in 2018, completing the CLARA Front-End, which consists of a S-band photo-injector gun and linac. Phase 1 produced electron bunches at 10 Hz, up to 250 pC in charge and with energy of 50 MeV. A comprehensive review of results from commissioning CLARA Phase 1 can be found in [1]. Phase 1 was used for two periods of competitively allocated beam exploitation, taking place in 2018/19 and 2021/22. A broad range of experiments were performed in these periods, including multiple experiments on novel acceleration techniques: dielectric wakefield acceleration, THz driven acceleration, and plasma wakefield acceleration. These novel acceleration experiments were performed in the CLARA Beam Area 1 (BA1) user hutch where a 100 mJ class laser system was available for exploitation with the electron beam [2].

Phase 2 of CLARA is currently under construction, comprising of an upgrade to the photo-injector gun and installation of 3 further linacs. This will produces bunches at 100 Hz, 250 pC with final energy of 250 MeV. Included in Phase 2 is the installation of the Full Energy Beam Exploitation (FEBE) hutch. The FEBE hutch represents a step change in experimental capability over BA1, benefiting from both the uplift in electron beam parameters and inclusion of a 100 TW class laser system. The FEBE beamline and hutch will be used for a broad range of experiments, and not exclusively novel acceleration applications. However, it is these novel experiments that pose the greatest challenge for machine performance in terms of beam parameters and subsequent instrumentation.

Phase 3 of CLARA is tied to the R&D requirements for a future UK-XFEL and is not yet funded.

FEBE BEAMLINE

The FEBE beamline is shown in Fig. 1 and comprises of a 4 cell FODO arc, transporting the beam to a shielded hutch with approximately 10×5 m^2 floor space. The room which houses the 100 TW laser system is on the roof directly above the hutch. A detailed discussion of the design of the FEBE beamline can be found in [3]. There are 4 chambers in the FEBE hutch: FMBOX1 for coupling and focusing the laser beam co-linearly with the electron beam, FEC1 ($\approx$ 2 m length) for the primary interaction point (IP) with the focus of both electron and laser beams, FMBOX2 for the dumping and diagnostics of the laser beam, and FEC2 as a secondary electron beam interaction point and for housing a suite of diagnostics. The FEBE beamline has an array of well developed or commercially available diagnostic systems including: Ce:YAG screens, stripline beam position monitors (BPMs), integrating current transformers (ICTs), and Faraday cups (F-cups).

The input electron beam parameters for FEBE are shown in Table 1. Beam parameters which are expected to be achieved following initial commissioning are shown, along with potential future parameters which could be achieved following dedicated machine development. Two charge modes are shown, a maximum charge of 250 pC and a low charge of 5 pC; which is the lowest the current BPM electronics will resolve. These parameters are not exhaustive or prescriptive and FEBE will offer very flexible beam setups to users, significantly improved over that provided to users of BA1. Table 1 also indicates those future parameters which will require diagnostics R&D to experimentally validate.

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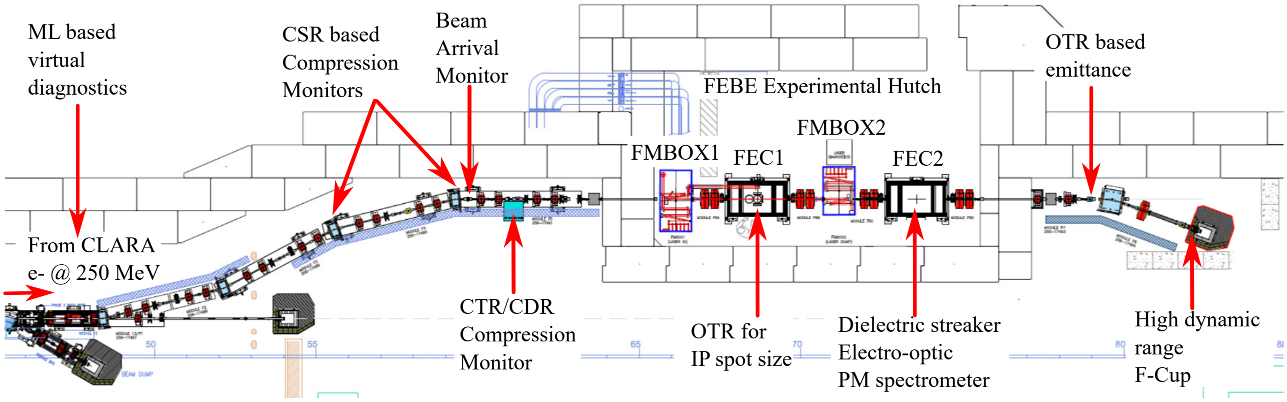

Figure 1: Engineering diagram of FEBE beamline, highlighting areas with diagnostic systems undergoing R&D. These areas are supported by diagnostic systems including Ce:YAG screens, beam position monitors and ICTs.

Table 1: Initial and future input FEBE beam parameters at the primary IP in FEC1. All parameters are for beam energy 250 MeV. Symbol σ_i indicates RMS value, $\epsilon_{N,i}$ indicates normalised RMS emittance. Parameters marked with † will require diagnostic R&D to validate.

Parameter	Initial		Future	
Charge (pC)	250	5	250	$< 5^\dagger$
σ_t (fs)	100	$50^\dagger$	$50^\dagger$	$< 50^\dagger$
σ_x (µm)	100	20	50	$\sim 1^\dagger$
σ_y (µm)	100	20	50	$\sim 1^\dagger$
$\epsilon_{N,x}$ (µm)	5	2	< 5	1
$\epsilon_{N,y}$ (µm)	5	2	$< 1^\dagger$	$< 1^\dagger$

R&D activities supporting making these measurements are highlighted in Fig. 1.

Beams accelerated within FEC1/2 of up to 600 MeV can be transported through the FEBE hutch to the final dipole and spectrometer line. Beams with energy in excess of 600 MeV and less than 2 GeV must be diagnosed and safely dumped in the hutch in FEC2.

6D DIAGNOSTICS R&D

There are several diagnostic systems under development to support measuring future beam parameters in FEBE and meet some of the unique challenges posed by beams from novel acceleration experiments, including: beams with high energy spread, unstable transverse and longitudinal properties, and exacting IP parameters which cannot drift during the experiment. This requires development of single shot diagnostics to monitor and feedback on machine drifts and instabilities in post IP accelerated beams, precise measurements of small focal spot sizes and arrival times, and systems capable of dealing with a large range of beam energies. A non-exhaustive list of current R&D activities at CLARA to meet these requirements is provided below.

PM Dipole Spectrometer

A permanent magnet (PM) dipole spectrometer has been designed for use in FEC2. This spectrometer will be able to measure beam energies in the broad range of 0.05 - 2 GeV, and will support measurement of beams with high energy spread and/or energy instability. The dipole is comprised of NdFeB blocks with a Ni-Cu-Ni coating (for vacuum compatibility) with a gap of 20 mm and a peak field of 0.72 T. It has a modular design, comprising of a total of 5 sections, such that the length of magnet installed can match the expected maximum beam energy. The physical extent of the full magnet, along with electron trajectories across its operating energy range, is shown in Fig. 2. A scintillating screen of 1 m in length and corresponding imaging system would be required to measure beams across the full range.

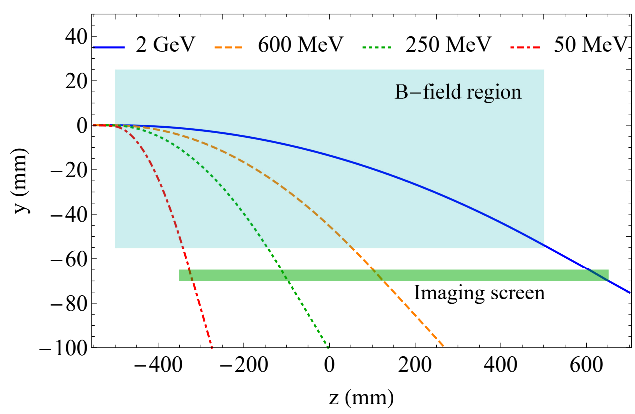

Figure 2: The physical extent of the full PM dipole system for use in FEC2, along with imaging screen. Electron trajectories for the full operating range are shown.

Dielectric Wakefield Streaker

A passive streaker based on a dielectric wakefield accelerator (DWA) structure has been designed to make bunch length measurements across the range of ~ 50 fs to > 1 ps. The streaker works through exciting dipole wakefields when the electron beam propagates off axis in a planar dielectric

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waveguide. Such passive wakefield devices have been shown to make accurate bunch length measurements at operational FEL facilities whilst costing a fraction of that of a RF transverse deflecting cavity (TDC) [4]. Recent studies of the properties of transverse wakefields in DWA structures which were performed in CLARA BA1 are reported in [5]. Along with dipole wakefields, higher order quadrupole-like modes are excited, which cause a non-linear variation in streaking force transversely across the bunch, resulting in reduced resolution of the bunch length measurement. The effect of these higher order wakefields can be negated through use of a second DWA structure orthogonally orientated to the first which increases the average resolution of the measurement across the bunch by a factor of ~ 3, this is shown through simulations in Fig. 3. It should be noted that the DWA streaker resolution does not scale favourably with reducing beam charge, and will not be able to resolve the bunch lengths at low charges.

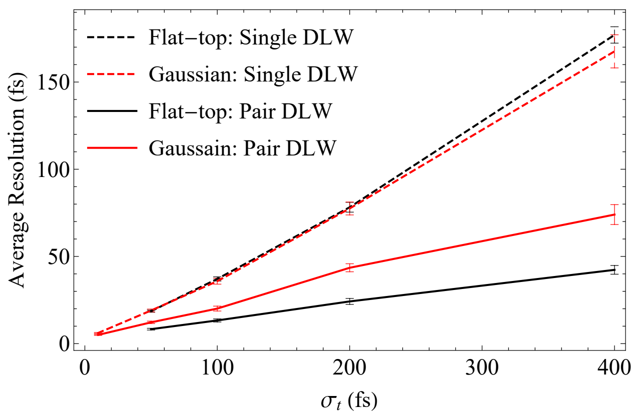

Figure 3: Simulated average resolution of a DWA streaking measurement in FEC2 for varying bunch length σ_t for both Gaussian and flat-top profiles (where flat-top has total length $4\sigma_t$), for charge of 250 pC. The improvement in resolution from using a pair of orthogonally orientated structures to cancel higher order wakefields is shown.

Electro-Optic Bunch Length Reconstruction

A system for bunch length reconstruction based on electro-optic spectral interferometry (EOSI) has been developed with proof of concept experiments performed in CLARA BA1. This non-invasive system used an optical non-linear crystal (gallium phosphide) to imprint the Coulomb field of the electron bunch onto the spectrum of a chirped laser pulse. The EOSI technique for retrieving the bunch profile from the spectrum was shown to have improved temporal resolution over the more conventional spectral decoding (SD) technique. Single shot bunch length measurements were made with bunch charges from 2 pC to 150 pC and down to σ_t = 300 fs. Measurements were possible with a transverse distance of 1 cm between the beam trajectory and the EO crystal at 100 pC. Future work will focus on development of a more robust fibre coupled system.

Coherent Radiation Bunch Compression Monitors

A coherent transition radiation (CTR) based bunch compression monitor (BCM) was installed and commissioned to support user exploitation in BA1 [1, 2]. This robust BCM was found to be valuable for machine tuning and reproducibility. An upgraded CTR BCM will be installed on FEBE, employing high and low pass filters in order to act as a rudimentary spectrometer, as is shown in Fig. 4. This system, combined with accurate measurements upstream in CLARA using a TDC, will ensure maximally compressed beams can be delivered to FEBE for novel acceleration experiments. In addition to the solid CTR target, a non-invasive coherent diffraction radiation (CDR) target - with a hole in the middle - can also be used to provide shot-to-shot compression jitter measurements. The detector is a bespoke pyroelectric based system, employing variable gain, active noise cancellation, and Winston cones for radiation capture. This detector will also be employed on the FEBE arc for measurement of coherent synchrotron radiation (CSR).

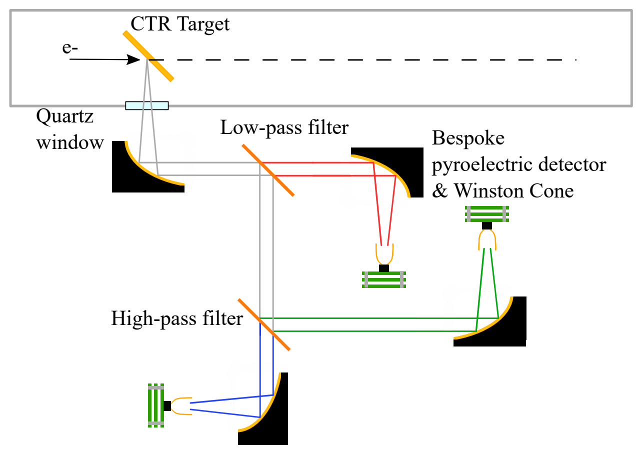

Figure 4: Schematic diagram of the BCM spectrometer system to be installed at end of FEBE arc as indicated in Fig. 1.

Beam Arrival Monitor and Laser Synchronisation

Measurement and reduction of time of arrival (TOA) jitter between the FEBE laser and the electron beam will be vital for laser driven acceleration experiments. The FEBE laser will be optically synchronised to the CLARA optical clock. Design and testing has been completed for producing a stabilised (<10 fs drift over 24 hours) in-fibre clock distribution system and testing is underway for providing two-colour laser locking. A new beam arrival monitor (BAM) is being developed with removable pick-ups in a similar design to [6]. The initial performance target is 10 fs resolution TOA measurement at a minimum of 20 pC, with a future goal of operation at < 5 pC with upgraded BAM pick-ups.

Development work is also progressing on a THz driven electron beam streaker. The THz source would be produced from optical rectification of the FEBE laser in a non-linear crystal, before mode shaping and coupling into a dielectric

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lined waveguide, as in [7]. This laser based streaker system would provide both precise TOA jitter measurements and bunch length measurements for the short, low charge beams shown in Table 1.

OTR Based Emittance Measurements

Imaging of optical transition radiation (OTR) is a well established technique for measuring transverse beam sizes and beam divergences. As both spatial and angular information from the electron beam is encoded in OTR, direct measurement of beam emittance is possible. This requires localising divergence measurements to discrete regions of the spatial OTR image; analogous to making an emittance measurement using a mechanical slit or "pepper-pot". Two techniques are under investigation to produce an OTR based "optical pepper-pot": optical masking using a digital micromirror device (DMD) [8], and imaging with a micro-lens array (MLA) [9]. Current effort is focused on development of bench-top prototype systems and improving accuracy of simulations performed in Zemax. Single shot emittance diagnostics have the potential to be highly impactful for novel acceleration experiments, as conventional multi-shot techniques (e.g. quadrupole scan) are not appropriate for unstable beams. An OTR based pepper-pot also scales favourably with increasing beam energy, in contrast to a mechanical mask.

Virtual Diagnostics

Machine learning (ML) based algorithms can be used to predict beam parameters at a given location from a set of input machine parameters the ML model has been trained on; this is referred to as a virtual diagnostic. Initial simulation studies for FEBE have shown accurate and precise prediction of the IP beam size from an image of a beam either up- or downstream of the IP, for a variety of lattice settings [10]. Prediction of the IP beam size will be vital for experiments where precise transverse diagnostics cannot be installed at the IP due to spatial or mechanical constraints. Future activities will seek to build on the results presented in [11] for longitudinal phase space prediction, and incorporate (simulated) measurements from the CSR/CTR BCM systems.

High Dynamic Range Charge Measurements

The flexible beam delivery of FEBE will require both accurate and precise measurement of charges from < 5 pC to 250 pC. Low charge machine setups will be important for the initial phases of some novel acceleration experiments, as the transverse spot sizes and bunch lengths will be significantly lower than at high charge, as shown in Table 1. A new electronics front end has been developed for the F-cups on CLARA which will maintain accuracy and a high signal-to-noise ratio across this charge range. Further details can be found in [12].

CONCLUSION

The FEBE beamline has a large number of diagnostics dedicated to making beam measurements across the full 6D parameter space. This large number of conventional and novel diagnostics will support both the initial commissioning of FEBE and reaching of its future potential for users. The active R&D efforts in both precision and single-shot diagnostics will benefit future novel acceleration experiments and support this community's efforts in delivering compact accelerators with high beam quality.

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REFERENCES

[1] D. Angal-Kalinin *et al.*, "Design, specifications, and first beam measurements of the compact linear accelerator for research and applications front end," *Phys. Rev. Accel. Beams*, vol. 23, p. 044 801, 2020. doi:10.1103/PhysRevAccelBeams.23.044801

[2] D. Angal-Kalinin *et al.*, "Status of CLARA at Daresbury Laboratory," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper THPOJO09, to be published.

[3] A. R. Bainbridge, D. Angal-Kalinin, J. K. Jones, T. H. Pacey, Y. M. Saveliev, and E. W. Snedden, "The Design of the Full Energy Beam Exploitation (FEBE) Beamline on CLARA," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2594–2597. doi:10.18429/JACoW-IPAC2022-THPOPT015

[4] P. Dijkstal *et al.*, "Self-synchronized and cost-effective time-resolved measurements at x-ray free-electron lasers with femtosecond resolution," *Phys. Rev. Res.*, vol. 4, p. 013 017, 2022. doi:10.1103/PhysRevResearch.4.013017

[5] Y. Saveliev *et al.*, "Experimental study of transverse effects in planar dielectric wakefield accelerating structures with elliptical beams," *Phys. Rev. Accel. Beams*, vol. 25, p. 081 302, 2022. doi:10.1103/PhysRevAccelBeams.25.081302

[6] A. Angelovski *et al.*, "Evaluation of the cone-shaped pickup performance for low charge sub-10 fs arrival-time measurements at free electron laser facilities," *Phys. Rev. ST Accel. Beams*, vol. 18, p. 012 801, 2015. doi:10.1103/PhysRevSTAB.18.012801

[7] M. T. Hibberd *et al.*, "Acceleration of relativistic beams using laser-generated terahertz pulses," *Nat. Photonics*, vol. 14, no. 12, pp. 755–759, 2020. doi:10.1038/s41566-020-0674-1

[8] G. P. Le Sage, T. E. Cowan, R. B. Fiorito, and D. W. Rule, "Transverse phase space mapping of relativistic electron beams using optical transition radiation," *Phys. Rev. ST Accel. Beams*, vol. 2, p. 122 802, 1999. doi:10.1103/PhysRevSTAB.2.122802

[9] F. Bisesto *et al.*, "Recent studies on single-shot diagnostics for plasma accelerators at sparc-lab," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 909, pp. 364–368, 2018. doi:10.1016/j.nima.2018.02.059

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO1C3

[10] J. Wolfenden *et al.*, "Application of Virtual Diagnostics in the FEBE Clara User Area," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper MOPORI05, to be published.

[11] M. Maheshwari, D. J. Dunning, J. K. Jones, M. P. King, H. R. Kockelbergh, and A. E. Pollard, "Prediction and Clustering of Longitudinal Phase Space Images and Machine Parameters Using Neural Networks and K-Means Algorithm," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3417–3420. doi:10.18429/JACoW-IPAC2021-WEPAB318

[12] S. Mathisen, T. Pacey, and R. Smith, "Analog Front End for measuring 1 to 250 pC Bunch Charge at CLARA," presented at IBIC'22, Krakow, Poland, Sep. 2022, paper MOP32, this conference.