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THE CLEAR USER FACILITY: A REVIEW OF THE EXPERIMENTAL METHODS AND FUTURE PLANS

P. Korysko*[1], M. Dosanjh, J.J. Bateman, C. Robertson, University of Oxford, Oxford, UK
R. Corsini, W. Farabolini, A. Aksoy, A. Malyzhenkov, V. Rieker, CERN, Meyrin, Switzerland
K. N. Sjobak, University of Oslo, Oslo, Norway
[1]Also at CERN, Geneva, Switzerland

Abstract

The CERN Linear Electron Accelerator for Research (CLEAR), operating since 2017, is a user facility providing electron beams for a large and varied range of experiments. The electron beam is produced from a Cs_2Te photocathode and is accelerated between 30 MeV and 220 MeV in a 20 m long linear accelerator. In 2022, several hardware and software tools were upgraded and novel procedures and methods were developed to address specific user requirements, including a further extension of the beam parameter ranges. In the paper, these improvements are described and the experimental activities during 2022/2023 are outlined. An outlook on future potential upgrades and on the planned experimental activities in the next years is also given.

INTRODUCTION

The CLEAR facility offers to its users electron beams with a large range of parameters [1–4], as shown in Table 1. In Figure 1 the time structure and charge parameters achievable in CLEAR are described and a diagram of the beamline is shown in Figure 2. Two in-air test areas are available in CLEAR: the first, called VESPER (Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments) is mostly used for electronics radiation hardness tests, while the second In-Air Test Area has a larger flexibility and hence is adapted to more general use. In practice, both areas have been used for medical applications studies like Very High Energy Electron (VHEE) radiotherapy at Ultra High Dose Rate (UHDR) [5] and others [6] and for the irradiation of electronics components [7–10]. In particular VESPER has been used to test and validate components for the ESA's JUpiter ICy moons Explorer (JUICE) mission, launched in April 2023. Other in-vacuum test areas are available to host specific experiments. All test areas are also used for novel accelerator technology studies like plasma lenses [11–13] or experiments aimed at development and testing of beam instrumentation [14].

CLEAR is not connected to the chain of proton machines at CERN. Thus it can run during LHC's long shutdowns and upgrades. The beam schedule is very flexible: typically the installation of the weekly experiments is done on Monday mornings and the accelerator can run from 8 to 12 hours per day, 5 days a week, depending on the needs of the users. The machine ran for 38 weeks in 2019, 34 and 35 weeks during the 2020 and 2021 COVID-19 crisis and 37 weeks in 2022. In September 2020 the CERN Council approved the CERN Medium Term Plan which included funds for extended CLEAR operation, then confirmed by the CERN management until end 2025.

* pierre.korysko@cern.ch

Table 1: Updated List of CLEAR Beam Parameters

Parameter	**Value**
Beam Energy	30 – 220 MeV
Beam Energy Spread	< 0.2% rms (< 1 MeV FWHM)
Bunch length rms	0.1 – 10 ps
Bunch frequency	1.5 or 3.0 GHz
Bunch charge	0.005 – 1.6 nC
Norm. emittance	1 – 20 μm
Bunches per pulse	1 – 200
Max. pulse charge	87 nC
Repetition rate	0.8333 – 10 Hz

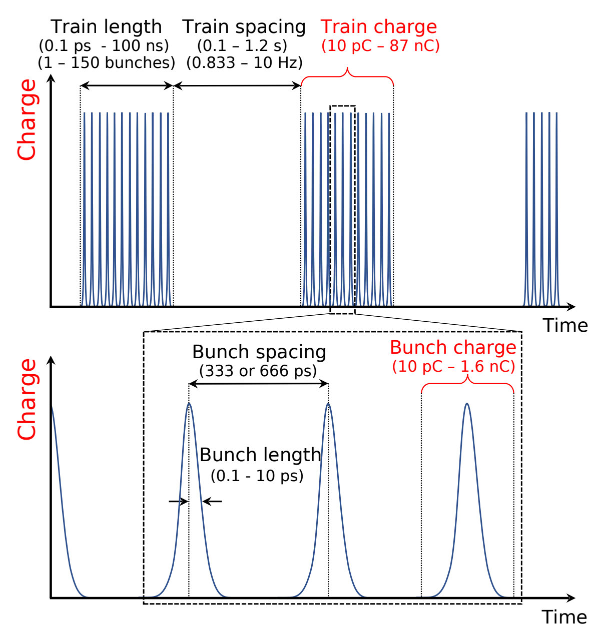

Figure 1: CLEAR beam time structure and charge parameters at the end of the beam line in 2023.

OPERATION AND PERFORMANCE

During the 2022/2023 period several modifications were done to the CLEAR beamline:

Three experiments were installed in-vacuum in the now called Beam Instrumentation (BI) test area: a Cherenkov

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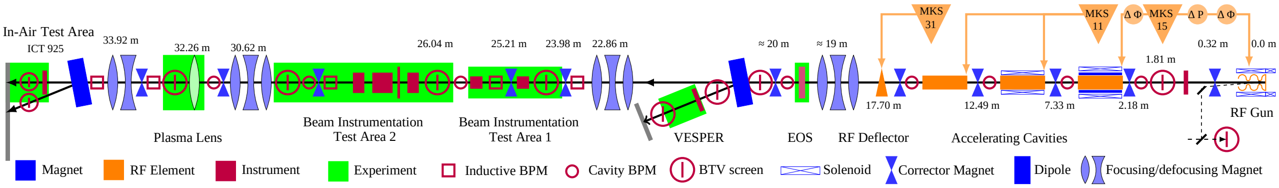

Figure 2: CLEAR beam line in 2023. Notice that the electron beam travels from right to left. [2]

Diffraction Radiation (ChDR) Bunch Length Monitor, a ChDR Beam Position Monitor (BPM) and an Electro Optical Spectral Decoding scheme based on ChDR to measure the bunch length.

The last quadrupole on the In-Air test stand (QDD0920) was removed. This quadrupole was used for Very High Energy Electron strong focusing studies in a water phantom. Transverse waists, corresponding to peaks in the dose delivered, were obtained in water at 3 different depths. This configuration might be used for future potential cancer treatment using electrons. The human body is represented in the experiment by the water phantom and the waist would be at the tumor location. Such an arrangement would concentrate the dose on the tumorous cells and spare the surrounding healthy tissues.

The CLEAR photocathode has been rejuvenated. A thin layer of Cs_2Te was deposited by evaporation on the cathode surface in order to restore the desired quantum efficiency. After the treatment, a bunch charge of 1.6 nC has become achievable.

The vacuum system was updated and consolidated, offering higher reliability and a better vacuum level in several locations along the beam line.

A CLEAR on-line optics model was developed, allowing the operators to easily estimate the impact of beam optics changes. This has proven really useful in order to set-up the magnets to control losses and to deliver a beam with the required parameters to the users.

The C-Robot [15–17] was used for more than 10 experiments in 2022. Designed, developed and built by members of the CLEAR team, this robotic system has been developed to easily irradiate numerous types of samples for medical applications. It is made of 3 linear stages for X,Y and Z axis, 6 limit switches (2 for each axis), a 3D printed grabber, a mounted-camera system with a moving filter and two tanks (one storage tank and one tank in the electron beam). One can move up to 32 different 3D-printed holders in the electron beam. Each of them can hold an Eppendorf tube in which samples are located. A new dedicated holder with a YAG screen was built. A mirror is angled by 45° compared to the electron beam installed after the screen and thanks to camera mounted on the C-Robot, the beam position and the beam size of the electron pulses can be measured in air and in water at any transverse and longitudinal position in the beam area. Rendered pictures of the C-Robot and the YAG screen holder are shown in Figure 3.

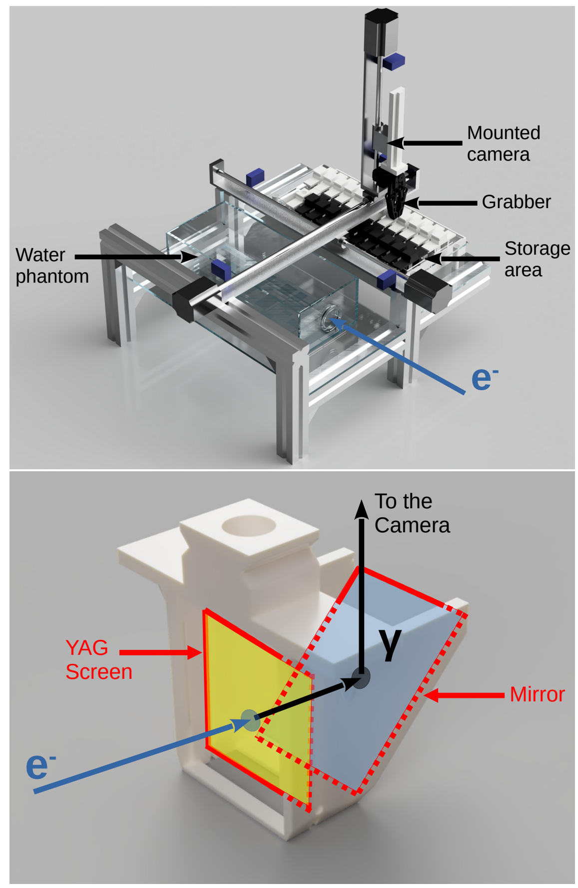

Figure 3: Rendered image of the C-Robot (top) and of the YAG screen holder (bottom).

EXPERIMENTAL PROGRAM IN 2022

The CLEAR experimental program has grown with time and more than 25 experiments were performed in CLEAR in 2022. More than 10 of them concerned medical applications (including testing and developing tools to deliver the right dose and electron beam shape and profile for VHEE radiotherapy, and studies of the FLASH biological effect at Ultra High Dose Rates with chemicals or biological samples), 5 involved beam instrumentation (bunch length and beam position measurements, beam loss monitors, etc.), 4 development of accelerator technology and 3 technical irradiations. Pictures, presentations and publications of all the experiments done in CLEAR can be found on the dedicated CLEAR Experiments web page [18]. Some details are given for selected experiments performed in 2022 in the following subsections:

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Beam Instrumentation

In 2022, 5 experiments on Beam Instrumentation (BI) development were performed. Three of them, using ChDR emission to measure the bunch length and the beam position, were installed in vacuum in the Beam Instrumentation Area. The instrumentation tested has been developed to be used in the Advanced WAKEfield Experiment (AWAKE) [19] and the Future Circular Collider (FCC). In CLEAR they have shown the capability to measure the bunch length with a precision of tens of femtoseconds and the beam transverse position with a precision of a few micrometers.

Several testing campaigns on a prototype of a Beam Loss Monitor based on the detection of Cherenkov light in optical fibres were carried out over the last years at CERN [20]. The system is aimed at measuring beam losses in the CERN Super Proton Synchrotron. Such prototype has been adapted and is now being used to help operation of the facility. Thanks to the new Beam Loss Monitor system, the beam losses can be localised in the machine with a 50 mm precision. A new graphical user interface, developed by A. Christie (Oxford University), shows in real time the position of the losses on a CLEAR map. This helps the CLEAR operators to optimise the beam transport really easily for any beam parameters (size, energy, charge, length, etc.).

Radiation to Electronics

More Radiation to Electronics (R2E) experiments were done in CLEAR in 2022. The goal is to verify the electronics components functionality in radiation environments, and better understand the underlying damage mechanisms. A few experiments were also using CLEAR as a neutron source: a tungsten target was placed in the electron beam to generate a controlled flux of neutrons. These neutrons were then used to either irradiate electronics in a controlled way or to test neutron detectors. Moreover, several measurement campaigns were done by the CERN Radio Protection (RP) group to test and benchmark numerous active and passive dosimeters.

Irradiations for Medical Applications

In collaboration with the Centre Hospitalier Universitaire Vaudois (CHUV), Oxford, Oslo, Manchester and Victoria Universities among others, more measurements were done in 2022 to study the use of VHEE beams at UHDR for cancer radiotherapy [21]. VHEE beams are a promising candidate for treating deep-seated tumours due to their highly penetrating dose distributions and lack of sensitivity to inhomogeneities.

In this framework, several passive [22] and real-time measurement methods were tested to measure the delivered dose: radiochromic films, radio-photo-luminescence dosimeters, diamond or silicon detectors, scintillating and optical fibres [23] or charge and beam profile measurements using standard accelerator diagnostics [24].

More measurements were dedicated to chemical (Oxygen Peroxide production in water) and biological studies (e.g., on Plasmids and Zebra-Fish Eggs), comparing effects of irradiation done at average and at ultra high dose rates. The main goal was to verify with VHEE the FLASH effect, the biological response to a very fast dose delivery which has been shown to partially spare healthy tissues, and to study details of its action mechanism.

EXPERIMENTAL PROGRAM IN 2023

More than 30 beam requests for CLEAR experiments were received so far for potential execution in 2023: 13 linked to medical applications (4 for beam delivery methods, 5 for testing instruments for dosimetry and 4 for studying the effects of VHEE at UHDR on chemical and biological samples), 13 concerning beam instrumentation and diagnostics, 5 on development of novel accelerator technologies including Plasma Lens studies, test of cold copper accelerating structures, inverse Compton scattering and a target and moderator system for neutron production.

CONCLUSION

CLEAR just entered its seventh year of operation and the experimental parameter range available to users, steadily growing in this period, is now even larger than in 2022. This wide beam parameter range makes CLEAR, among other things, a unique facility for VHEE and UHDR experimentation. CLEAR can now offer a higher pulse charge, a more stable beam, shorter bunches and longer bunch trains than previously obtainable. New tools and instruments are also available, in particular beam scatterers and collimators in order to obtain flat profile beams for VHEE studies, numerous types of holders for irradiation of samples, optical fibres for real-time dosimetry, etc. In the future, CLEAR plans to increase its flexibility, availability and reachable beam parameters with the installation of a second beamline dedicated in part to medical applications. A second source is being developed in a nearby experimental hall, and may also become available for beam tests. Finally, the reconnection of the CLEAR beam line to an existing X-Band Klystron/modulator station should enable to resume beam testing of high-gradient accelerating structures.

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