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STATUS OF THE CLEAR USER FACILITY AT CERN AND ITS EXPERIMENTS

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Abstract

The CERN Linear Accelerator for Research (CLEAR) at CERN is a versatile user facility providing a 200 MeV electron beam for accelerator R&D, irradiation studies for space, and medical applications. After successful operation in 2017-2020, CLEAR running was extended in 2021 for another 5-year period. In the paper we give a status of the facility, outlining recent progress in beam performance and hardware improvements. We report on beam operation over the last years and review the main results of experimental activities. Finally, we discuss the planned upgrades together with the proposed future experimental program.

INTRODUCTION

The CERN Linear Electron Accelerator for Research (CLEAR) user facility is composed of a 200 MeV electron linac followed by an experimental beamline, and it is operated at CERN as a multi-purpose facility with high availability, easy access and high-quality electron beams. Its main scientific goals are: a) perform R&D on accelerator components for existing and possible future machines at CERN, including beam instrumentation prototyping and high gradient RF technology; b) provide an irradiation facility with high-energy electrons, e.g. for testing electronic components or for medical studies on novel radiotherapy methods; c) conduct experiments on novel accelerating techniques, like electron-driven plasma and THz acceleration.

CLEAR also plays a role as a training infrastructure for the next generation of accelerator scientists and engineers.

The CLEAR facility provides an electron beam covering a large range of parameters [1–4] as shown in Table 1. A schematic layout of the beamline is shown in Fig. 1: the 200 MeV linac, composed by one RF photoinjector and three S-band accelerating structures, is followed by a 20m long experimental beam line which includes a diagnostics section and a first in-air spectrometer/test area (called VESPER, for Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments), a long section that can host several in-vacuum experiments and, just before the dump, a final in-air test stand with another spectrometer, where most of the experiments take place. The in-vacuum test areas are used for beam instrumentation R&D [5], high-gradient acceleration and linear collider related activities, and advanced accelerator technology studies like plasma lenses [6–8]. Both the in-air areas are intensively used for studies on medical applications of Very High Energy Electrons (VHEE), like conventional and FLASH radiotherapy and sterilisation of personal protective equipment [9, 10]. The other main area of application for the in-air test stands is radiation hardness testing for electronics components for accelerator and space applications [11–14]. In particular the VESPER area has been initially developed in order to test components of the ESA's JUpiter ICy moons Explorer (JUICE) mission [15].

CLEAR re-uses equipment of the former CLIC Test Facility, CTF3, and began beam operation in September 2017. It is a fully independent installation and runs independently from other accelerators of the CERN Accelerator Complex. Therefore, the facility can function also during LHC's long shutdowns and periodic upgrades. An yearly run typically includes 35 to 40 weeks of beam time. At the beginning of 2021, CLEAR operation, initially approved for a period of four years, was formally extended until the end of 2025.

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 – 3 nC
Norm. emittance	1 – 20 µm
Bunches per pulse	1 – 150
Max. pulse charge	75 nC
Repetition rate	0.8333 – 10 Hz

BEAM PERFORMANCE AND UPGRADES

The CLEAR operation team gradually extended the range of available beam parameters during the last years, following the requests made by user groups. For instance, the beam energy range was extended from the initial range (100-200 MeV) first up to 200 MeV and down to 60 MeV, and very recently further down to 30 MeV, although at the cost of reduced beam quality.

The combination of improvements to the laser, the photoinjector and to the beam transport have increased the maximum charge per bunch to 3 nC. The implementation of a double-pulse setup, obtained by splitting the laser pulse and delaying one of the pulses through a tunable optical line, allowed to accelerate two bunches (or trains) with adjustable

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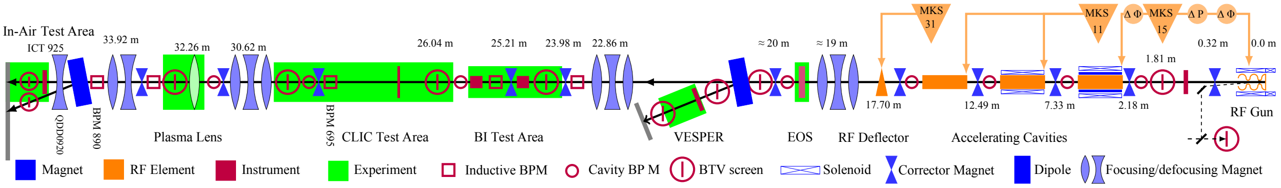

Figure 1: CLEAR beam line in 2022. Notice that the electron beam travels from right to left. [2]

distance in the same RF pulse. This system has been recently used to double the frequency of the bunch trains from 1.5 GHz to 3 GHz, and together with the increase in bunch charge allowed us to reach the record charge per pulse of 75 nC.

Several users require ultra-short bunches, with a duration of less than 1 ps, and sometimes of the order of 0.1 ps. Since the beginning, bunches in CLEAR were compressed using the velocity bunching technique, and ultra-short bunches were rapidly achieved and made available, down to the measurement resolution limit of 0.1 ps. However, the maximum charge for bunches of 1 ps or below was limited to 0.2 nC. A thorough simulation and experimental campaign allowed to reach the 1 ps level for bunches of about 1 nC, and to compress bunch charges of 0.5 nC down to 0.2 ± 0.1 ps [16].

A significant effort was made to improve the charge, position and size stability of the beam. Typically, the bunch charge and position is strongly correlated to the laser pulse intensity and position. Several improvements of the laser system, with a more accurate temperature control of the front-end, adjustments and re-alignment of the 75 m optical line and replacement of ageing components, have reduced the laser pulse pointing instability on the cathode down to 10 μm and reduced the power fluctuations and the corresponding beam charge jitter to $< 1\%$ rms, and 5% peak-to-peak.

Many improvements and modifications of the hardware, controls and software were also carried out in CLEAR since its first beam. We report below a few of the more recent ones, which took place in the 2021/2022 winter shutdown.

The CLIC cavity Beam Position Monitors (BPMs) and the CLIC structure were removed from the beam line. The resulting larger beam pipe aperture at their former locations lead to a better beam transport and an easier beam set-up. The cavity BPMs will be put back for tests in the next months, but can be removed afterwards. The CLIC structure will be put back in place when the X-band power source X-BOX1, presently under repair, will become again operational and available. A new quadrupole was installed in the In-Air Test Area. This quadrupole has been used for Very High Energy Electron (VHEE) strong focusing studies in a water phantom, described later.

The CLEAR photocathode has been renewed in 2021. A thin layer of Cs_2Te was deposited by evaporation on the cathode surface. This brought back the quantum efficiency to the percent level, allowing to reach again bunch charges well above 1 nC, after a degradation observed during the last run. Other consolidation work concerned the vacuum system, now offering higher reliability and a better vacuum level in several locations. Two optical fibers, object of previous R&D work in CLEAR, in collaboration with the CERN Beam Instrumentation group [17], were installed along the machine next to the beam pipe in order to measure beam losses and are being commissioned at present. The CLEAR on-line optics model has been also updated and improved.

A lot was done in order to improve the flexibility, efficiency and reliability of the in-air test station at the end of the beam line, especially for medical studies and R2E irradiation tests. In particular the CLEAR team designed, developed and built a robotic system called CLEAR-Robot (C-Robot), which can be used to manipulate samples and put them in and out of the beam trajectory for irradiation [18]. The robot can also position and insert into the beam a YAG screen to measure the beam position and the beam size at any transverse and longitudinal positions in the beam area. The C-Robot is fully open-source. Pictures, drawings, 3D renders and codes can be found on the C-Robot website [19] and on the C-Robot Gitlab Repository [20].

An essential component for irradiation studies, especially for medical applications, is a reliable and precise dosimetry. The development of dosimetry procedures and tools adapted to VHEE beams and especially to high dose rates has been the focus of a strong effort in CLEAR, in collaboration with several user groups. In particular, several methods of passive dosimetry, using Gafchromic films and Radio-Photo-Luminescence Dosimeter (RPL) were qualified [18], and real-time dosimeters like ionization chambers, diamond or silicon detectors are under investigation [21, 22].

MAIN EXPERIMENTAL RESULTS

The CLEAR experimental program covered a large number of experiments in several areas. More than 80 formal beam time requests were received since fall 2017, and the vast majority of them were completed. In the following we present some highlights.

Beam Instrumentation R&D

An extensive beam diagnostic R&D program was carried out in CLEAR in collaboration with the Beam Instrumentation group at CERN and a few external institutes [5]. In particular, issues related on the emission of diffraction and Cherenkov radiation and the production of radiation in the THz spectrum, and their use for beam monitoring purposes were addressed [23, 24]. The program included the development of Cherenkov Diffraction Radiation (ChDR) Beam Position Monitors (BPM) for the AWAKE experiment [25], beam loss detectors based on long optical fibers [17], dielectric ChDR pick-ups for LHC, micro Beam Profile Monitors for secondary beams and several others. In addition, studies on the improvement of bunch length measurement procedures when using an RF deflector were carried out [26].

Radiation to Electronics

Since its creation, the CLEAR beam has been often used for irradiation of electronic components (R2E), mainly to qualify their radiation hardness and explore the potential damage mechanisms [11]. Different effects were explored, from Single Event Upsets (SEU) [13] to Single Event Latchups (SEL) [12, 14], to recent studies on neutron production [27]. All these studies needed very different beam parameters, ranging from very low dose rates, obtained using only the dark current emitted by the cathode, to irradiation with the maximum pulse charge available at 20 Hz repetition rate. The VESPER beamline was used in collaboration with ESA to reproduce the radiation conditions within Jupiter's magnetosphere, which traps highly energetic charged particles in its massive magnetic field. Electronics for the JUICE mission were thus tested and validated in the high-radiation environment at CLEAR [15].

Novel Acceleration Methods - Plasma Lens

One of the main aims of CLEAR is to contribute to the development of novel acceleration technologies. The high-gradient CLIC accelerating cavities have been tested in CLEAR in passive mode, experimentally assessing their wake-field behaviour [28] and developing special wake-field monitors, on top of the CLIC cavity BPMs studies mentioned above. Several contributions were made as well to the AWAKE project at CERN, developing, as mentioned, special BPMs and performing the AWAKE spectrometer calibration [29]. Plasma lens technology opens up the possibility of using compact and very strong focusing devices for charged particle beams. Unlike magnetic quadrupoles, they focus the beam in both transverse planes simultaneously. Such lenses could replace quadrupoles in future applications, where small beams and compact dimensions are required, such as linear colliders or plasma-based accelerators. The main issues with such devices was the nonlinear aberration observed in some of the first experiments [30, 31].

The CLEAR Plasma Lens experiment investigated this issue and could show that for heavy gases plasma and/or early beam injection times such aberration, linked to non-uniform temperature distribution, would be avoided [7]. The more recent results obtained with the CLEAR Plasma Lens are described in [8]. With argon in a 500 μm diameter capillary, linear fields with a focusing gradient of 3.6 kT/m were obtained, an order of magnitude higher than the gradients of quadrupole magnets, establishing active plasma lenses as ideal devices for pulsed particle beam applications requiring very strong focusing.

Medical Applications

Although electrons are widely used to generate X-rays for radiotherapy, in general they are not directly used for irradiation. The small medical electron linacs used in hospitals for X-ray production have a limited energy reach, and low energy electrons can only be used directly for the treatment of superficial tumors given their low penetration range. However, the recent progress in high-gradient acceleration and the future perspectives of novel plasma-based facilities made possible the realization of very compact and possibly cheap machines. Thus, the use of Very High Energy Electrons (VHEE) for radiotherapy has gained interest.

Potential advantages are that the longitudinal dose deposition from VHEE is better than the one given by X-rays (although not as good as for protons), less sensitive than X-rays and proton beams to tissue inhomogeneities, and in addition the delivered electrons (as well as other charged particles) may be focused and steered in ways that are not possible for X-rays. Even more importantly, recent studies on ultra-high dose rate delivery of ionizing radiation (mean dose rate above 100 Gy/s), called FLASH radiotherapy (FLASH-RT), showed significant normal tissue sparing with respect to conventional radiotherapy, retaining tumour control. The FLASH effect seems to be present for all kinds of ionizing radiation, but the use of electrons looks particularly promising given the high current that can be delivered by electron linacs and the very high dose rates thus achievable.

The CLEAR user facility offered a unique opportunity for experimental VHEE and FLASH studies. Medical application experiments done in CLEAR include: a) Dosimetry for VHEE, in particular at Ultra High Dose Rates (UHDR), testing detectors and exploring the use of standard electron-beam diagnostics for real time dose rate evaluation [18, 21, 22]; b) Chemistry studies (e.g., Oxygen Peroxide production in water), c) Biological effects (e.g., on Plasmids and Zebra-Fish Eggs) at very high dose rates, with the goal to study the FLASH effect [32]; d) studies on VHEE dose deposition properties and optimization [33], including the use of focusing. The entrance dose due to VHEE beams could be reduced by focusing, concentrating the dose in the tumor area. The VHEE Strong Focusing experiments showed the possibility of having highly penetrating, focused VHEE at depths >10 cm into a water phantom [34].

OUTLOOK AND CONCLUSION

CLEAR just entered its sixth year of operation and the experimental parameter range available to users has been largely improved, making it, among other things, a unique VHEE and UHDR/FLASH test facility. New tools are also available, such as the C-Robot which offers a really versatile and adaptive instrument for irradiation experiments. The perspective of granted operation for a few years ahead allows to plan for even more substantial improvements, like a second beamline [16] to ensure more testing slots and the increased flexibility needed to satisfy ever growing user demand.

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