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FIRST EXPERIMENTS AT THE CLEAR USER FACILITY

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Abstract

The new "CERN Linear Electron Accelerator for Research" (CLEAR) facility at CERN started its operation in fall 2017. CLEAR results from the conversion of the CALIFES beam line of the former CLIC Test Facility (CTF3) into a new testbed for general accelerator R&D; and component studies for existing and possible future accelerator applications. CLEAR can provide a stable and reliable electron beam from 60 to 220 MeV in single or multi bunch configuration at 1.5 GHz. The experimental program includes studies for high gradient acceleration methods, e.g. for CLIC X-band and plasma technology, prototyping and validation of accelerator components, e.g. for the HL-LHC upgrade, and irradiation test capabilities for characterization of electronic components and for medical applications. An overview of the facility capabilities and a summary of the latest results will be presented.

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The new "CERN Linear Electron Accelerator for Research" (CLEAR) facility at CERN started its operation in fall 2017. CLEAR results from the conversion of the CALIFES beam line of the former CLIC Test Facility (CTF3) into a new testbed for general accelerator R&D and component studies for existing and possible future accelerator applications. CLEAR can provide a stable and reliable electron beam from 60 to 220 MeV in single or multi bunch configuration at 1.5 GHz. The experimental program includes studies for high gradient acceleration methods, e.g. for CLIC X-band and plasma technology, prototyping and validation of accelerator components, e.g. for the HL-LHC upgrade, and irradiation tests for characterisation of electronic components and for medical applications. An overview of the facility capabilities and a summary of the more relevant latest results are presented.

INTRODUCTION

The CLIC Test Facility CTF3 [1] ended its operation in 2016, after demonstrating the feasibility of the Compact Linear Collider (CLIC) key concepts [2, 3]. The expertise, space and equipment which were made available prompted the interest of a broad community, both within and outside CERN. The idea of reusing part of the CTF3 complex for a broader scope was explored in a dedicated workshop, held at CERN in October 2016 [4]. The CTF3 probe beam injector, called CALIFES [5], was identified as the most interesting, versatile and easily maintainable part [6]. A proposal to adapt and reuse CALIFES as an electron injector for a new test beamline was submitted to the CERN management and was approved in December 2016. The new stand-alone user facility is called CLEAR, for CERN Linear Electron Accelerator for Research, and its primary focus is general accelerator R&D and component studies for existing and future machines at CERN.

The experimental program covers two of the top priorities identified by the European Strategy for Particle Physics, namely the upgrade of the Large Hadron Collider and its injector chain (through prototyping and validation of accelerator components), and studies of high-gradient acceleration methods. The latter includes studies on normal conducting X-band structures and novel concepts as plasma and THz acceleration. CLEAR also provides unique training possibilities, as well as irradiation test capability in the VESPER test stand, developed in collaboration with the European Space Agency (ESA).

CLEAR BEAMLINES

The CLEAR facility is hosted in the CLEX experimental hall, approximately 42 m long and 7.8 m wide. The beamline is composed of the CALIFES injector, approximately 25 m long, followed by a 16 m-long beamline which can be easily adapted to suit the requirements of the users. The CLEAR injector is basically unchanged, except for a major upgrade of the RF system from a single to a double klystron. The electron beam is generated on a CsTe photo-cathode RF gun [7], followed by three LEP Injector Linac (LIL) 4.5 m-long accelerating structures [8]. The first structure can be used to compress the bunch length by velocity bunching and the gun and the first two structures are immersed in a solenoid field for focusing and space charge compensation. A matching section with a quadrupole triplet and a spectrometer line complete the injector. The RF network is composed by two independent 3 GHz modulators-klystrons [9] equipped with pulse compression systems [10]. Each klystron can provide up to 45 MW with 5.5 μs long pulses. The pulse compression allows to reach about 60 MW over 1.2 μs flat pulses or more than 120 MW peak power with short pulses. The first klystron feeds the gun and the buncher structure, and the RF amplitude and phase can be independently adjusted by an attenuator and two high-power phase-shifters. The last two structures are powered by the second klystron, while a third one is available to power the RF transverse deflector installed after the injector and used for bunch length measurements. The present layout of the experimental beamline after the CALIFES injector is depicted in Fig. 1, in which the beam travels from right to left.

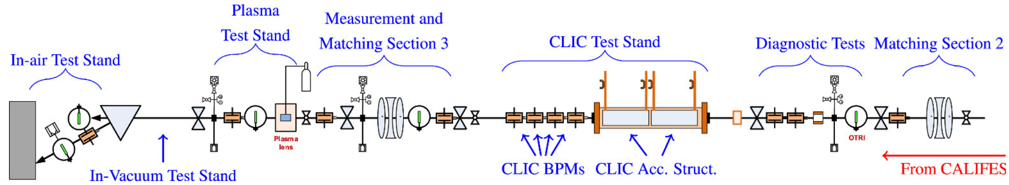

Figure 1: Schematic layout of the experimental beamline of CLEAR.

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After a matching section with a quadrupole triplet, a 2-m long section is used for beam instrumentation tests and presently hosts a chamber for Optical Transition (Diffraction) Radiation Interferometry (OTRI/OTDRI) studies [11]. In the following X-band test stand a CLIC accelerating structure and three CLIC cavity BPM prototypes are installed on the supports of the former CTF3 two-beam module, whose position can be actively controlled with a few μm precision. This allows for the continuation of Wake Field Monitor (WFM) [12], and high-resolution BPMs [13] studies. In particular a detailed study of the transverse kicks from dipole modes in the CLIC structure should clarify issues on the precise location of the electrical centre of the structure by WFMs.

A matching section is then used to adjust the beam parameters before the part of the beam line currently hosting a plasma lens experiment [14]. Before the final spectrometer, another 1.5 m long space can be made available for users. The beamline ends about 20 cm after the spectrometer dipole with a 100 μm thick aluminium window, leaving about 1 m long in-air path. This area, equipped with a $1.2 \times 0.9\ m^2$ optical table, is well suitable for fast installation and test of equipment that does not need to be operated under vacuum. Presently it hosts Cherenkov and THz radiation studies [15, 16]. In the rest of this paper we will focus on beam performance and on a few experiments for which relevant results were obtained in the relatively short beam-time delivered so far by the CLEAR facility. The other experiments mentioned above are ongoing and final results are expected soon.

OPERATION AND PERFORMANCE

The hardware modifications of the CALIFES beamline started in January 2017 and were completed over summer. The first beam was delivered to users at the beginning of September 2017. CLEAR operated with beam for a total of 19 weeks last year, and operation restarted in 2018 on the 22 February. About one third of the beam time has been dedicated to re-commissioning and beam development activities, the rest being granted to user experiments. The facility typically operates about 10 hours per day and it's stopped during week-ends, with the exception of irradiation studies in VESPER, where in most cases the possibility of unmanned operation allows for night and week-end runs. The main beam parameters obtained so far are summarized in Table 1. Beam studies are ongoing in order to extend the parameter range following requirements from users and making the best use of the hardware.

Table 1: CLEAR Beam Parameters

Parameter	Value Range	Unit
Energy	50 – 220	MeV
Bunch Charge	1 – 1500	pC
Norm. emittance	3 – 20	μm
Bunch length rms	200 – 10000	fs
Energy spread rms	< 0.2	%
Repetition rate	0.833 – 5	Hz
N. of bunches	1 – 200	

In particular, with respect to the typical parameters obtained in operation for CTF3, the energy range was already extended down to 50 MeV and the repetition rate for dark current operation increased to 10 Hz, as required by some irradiation tests. One fundamental request from many users is short bunches. Contrary to the old CALIFES installation, use of two independent RF power sources allows to fully optimize the velocity bunching. An optimization study in March 2018, making use of the transverse RF deflector as longitudinal diagnostics, measured bunches with rms lengths of about 200 fs, at the resolution limit of the device and five times shorter than what was measured before.

IRRADIATION TESTS IN VESPER

The Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments (VESPER) is located in a spectrometer beamline of the CLEAR facility, right after the CALIFES injector. The initial purpose of this in-air test stand, depicted in Fig. 2, is the characterization of electronic components for the operation in a Jovian environment – as foreseen in the JUpiter Icy Moon Explorer mission (JUICE) of ESA, in which trapped electrons of energies up to several hundred MeVs are present with very large fluxes. The scope of the installation was then extended to testing of other electronic components and to dosimetry for medical applications.

Radiation to Electronics Studies

The initial tests, including the validation of the installation and the first experimental evidence of electron-induced single event upsets (SEU), took place already in CALIFES during 2016 [17]. The tests in collaboration with ESA started during 2017 after an upgrade of the test stand and of the beam capabilities. Initial results, done at 200 MeV on the ESA SEU reference monitor (four SRAM memories on a single board with 0.25 μm chip technology), suggested that the large electron fluxes in the trapped radiation belts in the Jovian environments will indeed have a sizable contribution to the SEU rate of electronic components used in the JUICE mission [18]. Further tests were carried out over a larger energy range (from 60 MeV to 200 MeV) and extended to new generation devices, showed a dependency of cross-section with energy, while the cross-section remained constant with varying flux thus excluding prompt dose effects.

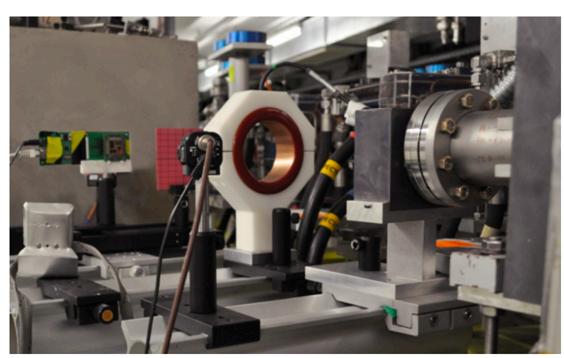

Figure 2: The VESPER test stand.

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A higher sensitivity of up to factor 10 was also ob-served for more integrated devices (28 nm technology) and demands further investigations [19]. A preliminary test on a set of memories sensitive to the latch-up effect has also shown that electrons can cause destructive events. Further tests on more integrated technologies (16 nm FinFET) were performed by ESA and their contrac-tors IROC in March 2018 and the data are now being analysed.

Very High-Energy Electrons for Cancer Therapy

Recent advances in compact high-gradient accelerator technology, largely prompted by the CLIC study, renewed the interest in using very-high energy electrons (VHEE) in the 50 – 250 MeV energy range [20] for radiotherapy of deep-seated tumours, currently treated using photon radiotherapy. Present day medical linacs deliver electrons in the 5 – 25 MeV range, suited to treatment of only superficial tumours. Higher energy electron beams penetrate deeper and might have potential advantages over conventional photon beams (higher dose reach, more conformal dose deposition, higher dose rate and the possibility for magnetic beam steering). Understanding the dosimetry of such beams is essential in order to assess their viability for treatment, and for this reason a group from the Uni-versity of Manchester proposed and carried out studies in the VESPER installation on energy deposition in water phantoms [21]. A series of measurements were done in 2017 using a set of EBT3 Gafchromic films submerged in water and irradiated at various depths in a 30 × 30 × 30 cm^3 phantom. The dose deposition profile was evaluated by Monte Carlo tracking simulations and compared with the measured one. Differences between measured and simulated dose profiles and beam spread curves were < 5%. In order to determine the sensitivity to different me-dia, longitudinal dose profiles with and without inserts of various density materials were measured.

The results showed that the dose profile and the electron beam spread are relatively unaffected by both high-density and low-density media, and the measured and simulated doses were consistent with each other also in this case. The obtained results indicated that VHEE has the potential to be a reliable mode of radiotherapy for treating tumours also in highly inhomogeneous and mobile regions such as lung. Further studies on the dose distribution of a converging beam as opposed to a parallel wide beam, and possibly on multi-angle irradiation are planned for the future.

THE PLASMA LENS EXPERIMENT

Active plasma lenses are a promising new technology for strongly focusing charged particle beams, and their compact size is an advantage for potential use in combination with novel high gradient acceleration methods. Still, many questions remain on such lenses, e.g., their transverse field uniformity and the limitations due to beam excitation of plasma wake-fields.

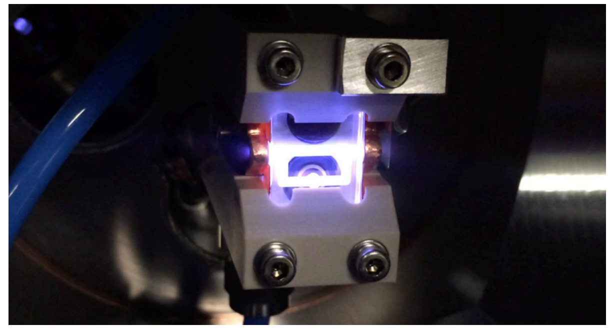

Figure 3: The plasma lens capillary in operation.

These questions are being addressed in the plasma lens experiment at CLEAR by a collaboration lead by Oslo University and including CERN, DESY and Oxford University [14].

The lens is located in a 20 × 20 × 20 cm^3 cubic aluminium vacuum chamber, and is composed of a 1 mm diameter, 15 mm long sapphire capillary tube. In Fig. 3 a photo of the capillary during a discharge is shown. Two gas inlets deliver either He of Ar gas at local pressures of up to 30 mbar or 70 mbar respectively. The gas is ionized by a 500 A peak current discharge with a duration of up to a few hundred ns, provided by a 20 kV spark-gap compact Marx bank generator. The longitudinal discharge current is responsible as well for the transverse focusing force in both planes. The capillary can be moved transversally using a precision two-axis mover with about one µm resolution and a 13 × 8 mm (h × v) range.

The lens was rapidly put in operation in autumn 2017, showing a clear focusing effect. Extensive measurements were taken during December 2017 and March 2018. In particular, evidence of non-linear self-focusing at relatively high bunch charge (~ 50 pC/bunch) was observed, while transverse position scans of a pencil beam revealed gradients of ~ 350 T/m. Further measurements are planned in order to validate and extend the studies done so far.

CONCLUSION

The CLEAR user facility, devoted to R&D for accelerators and related applications, started operation in autumn last year, and delivered already important scientific results in several areas, from radiation hardness tests of electronic components for satellites to studies on medical applications of electron linacs, to novel methods of beam acceleration and focusing using plasma.

Other experiments are ongoing or in preparation, on advanced beam diagnostics R&D, wake-field kick and impedance measurements and on the production and use of THz radiation. In parallel, beam performances are constantly being improved, e.g., reaching short bunches (~ 200 fs), as well as the range of parameters covered by the facility. Consolidation of a few sub-systems and upgrades (e.g., the connection to a high-power X-band klystron foreseen for summer 2018) are also planned, and the facility have the potential of providing other important results in the near future.

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