CONSOLIDATION AND FUTURE UPGRADES TO THE CLEAR USER FACILITY AT CERN

L. A. Dyks*[1], P. N. Burrows, P. Korysko[1], JAI, University of Oxford, Oxford, UK
R. Corsini, S. Curt, W. Farabolini, D. Gamba, L. Garolfi, A. Gilardi[2],
E. Granados, G. McMonagle, H. Panuganti, CERN, Geneva, Switzerland
K. N. Sjobak, University of Oslo, Oslo, Norway
[1]also at CERN, Geneva, Switzerland
[2]also at University of Napoli Federico II, Napoli, Italy

Abstract

The CERN Linear Electron Accelerator for Research (CLEAR) at CERN has been operating since 2017 as a dedicated user facility providing beams for a varied range of experiments. CLEAR consists of a 20 m long linear accelerator (linac), able to produce beams from a Cs_2Te photocathode and accelerate them to energies of between 60 MeV and 220 MeV. Following the linac, an experimental beamline is located, in which irradiation tests, wake-field and impedance studies, plasma-lens experiments, beam-diagnostics development, and terahertz (THz) emission studies, are performed. In this paper, we present recent upgrades to the entire beamline, as well as the design of future upgrades, such as a dogleg section connecting to an additional proposed experimental beamline. The gain in performance due to these upgrades is presented with a full range of available beam properties documented.

INTRODUCTION

The CLEAR user facility provides a flexible electron beam with a wide parameter range to its users [1–4]. A diagram of the beamline is shown in Fig. 1. Following the linac section, there is the VESPER test area, used for the irradiation of electronics [5–8], and for medical research into Very High Energy Electron radiotherapy (VHEE) and the sterilisation of personal protective equipment [9, 10]. Following VESPER, there are several other test areas used for experiments into high-gradient X-band acceleration technology [11, 12], beam instrumentation [13], and research into novel accelerator technology such as the use of plasma lenses [14–16] and the generation of THz radiation [17, 18]. Several beam diagnostics are installed on the beamline [19].

CLEAR operates a flexible beam program, approximately 9 hours a day, 5 days a week with a scheduled beam access every Monday morning. Operating as a stand-alone facility, thus operational during CERN's long shutdowns, CLEAR was in operation for 38 weeks during 2019, with a technical shutdown in the summer, and 34 weeks during 2020, despite Covid-19 disruption. The continuation of CLEAR operation has been provisionally extended until 2025 in the CERN Medium Term Plan approved by the CERN Council in September 2020.

Table 1: Updated List of CLEAR Beam Parameters

Parameter	Value
Energy	60 – 220 MeV
Energy Spread	< 0.2% rms (< 1 MeV FWHM)
Bunch length rms	0.1 – 10 ps
Bunch charge	0.001 – 3.0 nC
Norm. emittance	1 – 20 µm
Bunch frequency	1.5 GHz
RF frequency	3.0 GHz
Bunches per pulse	1– ~ 150
Max. pulse charge	30 nC
Repetition rate	0.8333 – 10 Hz

BEAM PERFORMANCE UPGRADES

In order to continue to reach the needs of present and future users, the beam parameter range and general beam performance are constantly being improved. The most recent set of beam parameters can be found in Table 1.

Beam Stability

Significant effort has been made into improving the stability of the beam, mostly directed towards the photoinjector [20]. Typically, the bunch charge is strongly correlated to the laser power incident on the photocathode. New, more accurate temperature controls have been installed on the front-end of the laser, which help to mitigate the long term drifts seen in laser power. The optical line from the laser lab to the photocathode has been surveyed, and adjusted, and through careful setup of the magnification of the laser beam, the beam pointing instability on the cathode, following the entire 75 m optical line, was reduced to 10 µm.

Several ageing components have been replaced in the laser system, which have reduced the laser power jitter [21]. The charge jitter caused by fluctuations in the laser power can be reduced further by saturating the photocathode, with no correlation between laser power and charge seen for a highly saturated cathode. Through these improvements charge fluctuations can now been reduced to < 1% rms, and 5% peak-to-peak with careful setup.

High-Charge Operation

In addition to increased stability, both the maximum bunch, and total train charge have been increased. The im-

---

* luke.dyks@physics.ox.ac.uk

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

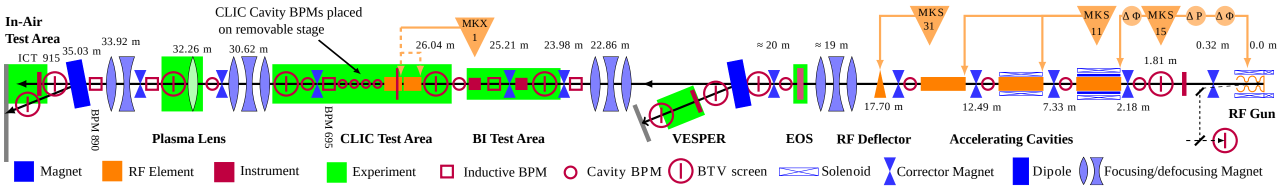

Figure 1: A diagram of the CLEAR beamline correct as of May 2021. Positions given refer to the centre of each element [22].

proved temperature controls, in conjunction with a new diode in the front-end laser, have increased the micropulse energy, with a potential maximum of 1.5 µJ demonstrated. In addition a new Cs_2Te photocathode has been installed in the gun with a quantum efficiency of ~4%.

Previously, several beamline elements were poorly aligned, meaning that a large amount of beam steering was required to prevent beam losses, especially when operating with high bunch charge. Therefore, effort has gone into aligning beamline components using a laser directed through the centre of the beam pipe. The combination of improvements to the photoinjector and alignment have increased the maximum charge per bunch achieved to 3 nC and the maximum charge per train to 30 nC, with the additional benefit of faster beam set up. To aid beam transport further, the CLIC cavity BPMs have been mounted on a removable stage, removing the aperture restriction they caused.

High-Charge Bunch Compression

Some users require ultra-short bunches of less than 1 ps in length, and often less than 0.1 ps. Bunches in CLEAR can be compressed using the velocity bunching technique, by de-phasing the RF field in the first RF cavity, relative to the peak acceleration phase. Ultra-short bunches have previously been achieved. However, due to high beam losses when compressing, the maximum charge for which this compression was achieved was 0.2 nC.

In order to investigate the possibility of producing compressed bunches of a higher charge, simulations of the CLEAR injector beamline were undertaken using the ASTRA code [23]. The full ASTRA model of CLEAR can be found at [24]. The beam was simulated using a laser pulse length of 4.7 ps and spot size varied between 0.4 mm and 1.2 mm. Initially the phase of the RF gun was set to the phase of maximum acceleration. By optimising the phase of the bunching cavity, it was shown that bunch compression to less than 1 ps should be possible up to a charge of 2 nC. The minimum bunch lengths achievable in simulation with the gun on crest energy phase are shown in Fig. 2. For compression of bunches of higher charge a larger laser spot is required to reduce space-charge forces in the gun, which cause bunch length growth. When bunches were compressed in simulation there was a significant increase in the transverse emittance, which could result in beam losses. It was shown in simulation that optimisation of the strengths of the solenoid magnets could suppress this growth effectively.

Following these simulations, experimental studies of high-charge bunch compression were undertaken, with care taken to adjust the strength of the solenoid and corrector magnets to improve transport. The bunch lengths were measured with the RF deflecting cavity and screen BTV390. There was reasonable agreement to simulation in bunch length at different buncher phases, an example is shown in Fig. 3. The highest bunch charge compressed to less than 1 ps was a bunch of charge 0.8 nC produced from a laser spot of 0.5 mm, which was compressed to a length of 0.8 ± 0.2 ps.

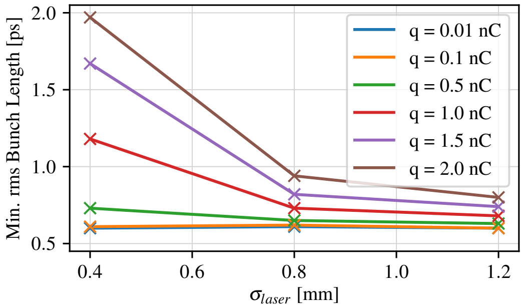

Figure 2: The minimum bunch lengths achievable for bunches of different charges generated from laser spots of different size simulated in ASTRA.

By de-phasing the gun, it was shown in simulation that even more compression could be achieved. By doing this experimentally, bunches of charge 0.3 nC and 0.5 nC were compressed to lengths of 0.1 ± 0.1 ps and 0.2 ± 0.1 ps respectively.

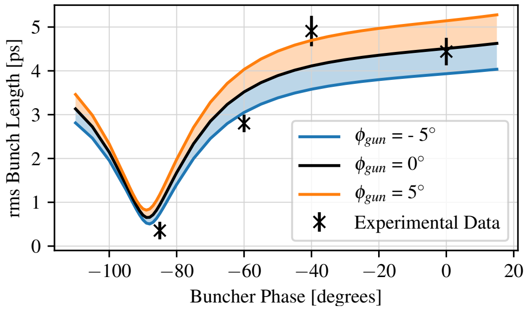

Figure 3: Comparison between ASTRA simulation and experimental data of the bunch length of a bunch charge 0.5 nC produced from a laser spot of 0.6 mm. A range of ±5° in simulation is shown.

BEAM DIAGNOSTIC IMPROVEMENTS

To complement the consolidation of beam performance, several improvements have been made to beam diagnostics. Studies have been undertaken into improving the accuracy of bunch length measurements with the RF deflecting cav-

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ity [25, 26]. It was shown that employing a focusing element between the deflecting cavity and measurement screen does not corrupt the measurement method. Using this technique the resolution of bunch length measurements on CLEAR has been improved to ~ 0.2 ps. In addition, a novel measurement procedure for investigating correlations between the longitudinal and transverse divergence has been developed, as well as a novel technique to measure the energy spread and energy chirp of the beam.

Several digital cameras are now in use on CLEAR. One is used on screen BTV620 to improve the resolution of beam profile measurements before the CLIC structure. There are also up to four installed on the in-air test stand at any one time to aid the resolution beam profile measurements for irradiation experiments. The digital cameras were able to perform well in the CLEAR environment, giving improved quality and resolution compared to their analogue equivalent [27]. Use of these cameras has allowed the reduction in the standard error of beam size measurements. A new control system is being developed for digital cameras, which will allow additional digital cameras to be installed phasing out the use of analogue cameras.

The five inductive BPMs installed have recently been commissioned to provide charge and position measurements to the operators. Charge calibration was performed against the Bergoz ICTs installed, and position calibration was performed using adjacent BTV screens. The BPMs were originally designed for use in the CTF3 drive beam [28], and their electronics were modified to work at the relatively low charges available on CLEAR. Currently they are not sensitive to short bunch trains, so further optimisation will be explored. Previously BPM 890 was installed on the spectrometer of the in-air test stand, it has been moved to its present position to provide additional experimental space. BPM 700 has recently been installed after the CLIC structure to provide position measurements for wakefield monitor studies.

SECOND EXPERIMENTAL BEAMLINE

In order to expand the number of user test stands available, a second experimental beamline has been proposed. The beamline would branch off from the CLEAR injector via a dogleg chicane at the existing VESPER dipole, and would provide a second in-air test stand as well as space for in-vacuum experiments to be installed. Furthermore, the dogleg could be configured to provide bunch compression to the beam to produce ultra-short bunches. The optics of the second beamline could also be configured to allow the use of larger aperture quadrupoles for the irradiation of larger target areas or strong focusing of the beam onto the target. In order to reduce costs the second beamline will reuse magnets and equipment currently installed in the old CTF3 beamlines as much as possible.

An initial proposal for the beamline is illustrated in Fig. 4. As sub-ps bunch compression has been demonstrated using the velocity bunching technique, the dogleg has initially been designed to provide the largest experimental space possible. The distance between the beamlines is 2 m, providing space for operator access and the installation of equipment. A bend angle of 20° has been proposed, which allows for a new beamline of 8.2 m. Two quadrupole magnets are proposed to be installed onto the dogleg in order to eliminate the chromatic terms, R_{16} and R_{26}. The optics of the beamline were studied using MADX. With this bend angle, the R_{56} of the dogleg was calculated to be −0.0192 m. By simulating the CLEAR injector using the ASTRA model, then using the MADX transfer matrix, it is suggested that a bunch of charge 0.5 nC could be compressed to a length of 0.26 ps. The effects of space charge and coherent synchrotron radiation will need to be investigated. The new experimental line would have two optics matching sections that are yet to be fully optimised. There would likely be space for a small in-vacuum experiment to be installed. A detailed design of the beamline will be completed by the summer of 2021 with the costs and feasibility considered in the autumn.

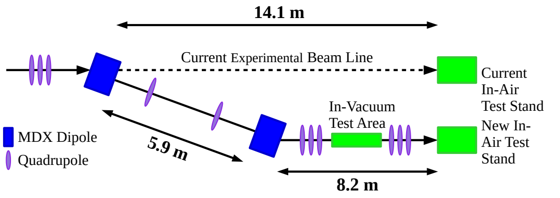

Figure 4: Illustration of an initial layout for the 2nd beamline.

FURTHER PLANNED UPGRADES

In collaboration with the AWAKE project and the INFN-Frascati National Lab, a new RF gun has been built [29]. The gun is currently undergoing commissioning which should be finished by 2022. The gun is currently planned to be installed at AWAKE for the second run in 2026. It would, therefore, be possible to use the gun in CLEAR to provide an additional electron source, either within the current beam hall, or for an independent beamline in the CTF2 hall.

The connection of the Xbox-1 X-band RF station to the CLIC structure was initially planned for 2019, but was delayed due to faults in the klystron [30–32]. The klystron is now undergoing conditioning, and its future use, either connected to the CLIC structure installed on CLEAR or for an independent beamline with the new particle source, will be decided later in 2021.

CONCLUSION

As CLEAR enters its fifth year of operation the experimental parameter range available to users is larger than ever. We are now able to produce shorter bunches, higher charge bunches, and longer bunch trains, all with a greater level of stability and measured with more precision. In future, we plan to further increase our parameter range with a second beamline, a second source, and potentially installing the Xbox-1 klystron.

REFERENCES

[1] CLEAR official website, http://clear.web.cern.ch/.

[2] K. N. Sjobak *et al.*, "Status of the CLEAR Electron Beam User Facility at CERN", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 983-986. doi:10.18429/JACoW-IPAC2019-MOPTS054

[3] R. Corsini *et al.*, "First Experiments at the CLEAR user facility", in *Proc. IPAC'18*, Vancouver, BC, Canada, 2018, pp. 4066-4069. doi:10.18429/JACoW-IPAC2018-THPMF014

[4] D. Gamba *et al.*, "The CLEAR user facility at CERN", *Nucl. Instr. Meth. Phys. Res. A*, vol. 909, pp. 480–483, Dec. 2017. doi:10.1016/j.nima.2017.11.080

[5] M. Tali *et al.*, "Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs", *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1715–1723, Aug. 2018. doi:10.1109/tns.2018.2843388

[6] M. Tali *et al.*, "Mechanisms of Electron-Induced Single-Event Latchup", *IEEE Trans. on Nucl. Sci.*, vol. 66, no. 1, pp. 437–443, Jan. 2019. doi:10.1109/iolts.2006.6

[7] A. Coronetti *et al.*, "SEU characterization of commercial and custom-designed SRAMs based on 90 nm technology and below", *2020 IEEE Radiation Effects Data Workshop*, 2020, pp. 1-8, doi:10.1109/REDW51883.2020.9325822

[8] A. Coronetti, R2E activities at CLEAR, presented at the CLEAR review 2021, https://indico.cern.ch/event/1015632/contributions/4262430/.

[9] R. Corsini *et al.*, "Status of VHEE Radiotherapy Related Studies at the CLEAR User Facility at CERN", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper WEPAB044, this conference.

[10] L.A. Dyks *et al.*, "Preliminary irradiation tests of surgical masks with 200 MeV electrons at CLEAR" CERN, Geneva, Switzerland, EDMS No. 2477002, Feb. 2021.

[11] S. Stapnes, Linear Collider and High Gradient Studies, presented at the CLEAR review 2021, https://indico.cern.ch/event/1015632/contributions/4262431/.

[12] P. Arpaia, R. Corsini, A. Gilardi, and K. N. Sjobak, "Beam-based alignment of the CLIC high-gradient X-Band accelerating structure using beam-screen", in *Proc. Int. Instrum. Meas. Tech. Conf.*, May 2019, pp. 1-6, doi:10.1109/I2MTC.2019.8827121

[13] S. Mazzoni, Beam Diagnostics R&D, presented at the CLEAR review 2021, https://indico.cern.ch/event/1015632/contributions/4262518/.

[14] C. A. Lindstrøm *et al.*, "Emittance Preservation in an Aberration-Free Active Plasma Lens", *Phys. Rev. Lett.*, vol. 121, no. 19, p. 194801, Nov. 2018. doi:10.1103/physrevlett.121.194801

[15] C. A. Lindstrøm *et al.*, "Overview of the CLEAR plasma lens experiment", *Nucl. Instr. Meth. Phys. Res. A*, vol. 909, pp. 379–382, Nov. 2018. doi:10.1016/j.nima.2018.01.063

[16] K. N. Sjobak *et al.*, "Multi-kT/m Focusing Gradient in a Linear Active Plasma Lens", arXiv, 2020. arxiv:2012.10680

[17] A. Curcio *et al.*, "Diffractive shadowing of coherent polarization radiation", *Phys. Lett. A*, vol. 391, p. 127135, 2021. doi:10.1016/j.physleta.2020.127135

[18] A. Curcio *et al.*, "Beam-based sub-THz source at the CERN linac electron accelerator for research facility", *Phys. Rev. Accel. Beams*, vol. 22, no. 2, Feb. 2019. doi:10.1103/physrevaccelbeams.22.020402

[19] H. Guérin, "Development and Implementation of Diagnostics for the CLEAR Facility", Ph.D. thesis, PHELMA, Grenoble, France, INP, 2018.

[20] E. Granados *et al.*, "Capabilities and performance of the CLEAR facility photo-injector laser", CERN, Geneva, Switzerland, Rep. CERN-OPEN-2020-002, 2019.

[21] E. Granados, "Upgrade of the CLEAR diode-pumped Nd:YLF power amplifier", CERN, Geneva, Switzerland, CERN-OPEN-2020-001, 2020.

[22] CLEARLayout, https://gitlab.cern.ch/CLEAR/clearlayout

[23] K. Floettmann, A Space Charge Tracking Algorithm, Hamburg, Desy, 2000, https://www.desy.de/~mpyflo/.

[24] CLEARAstra, https://gitlab.cern.ch/CLEAR/CLEARAstra

[25] P. Arpaia *et al.*, "Enhancing particle bunch-length measurements based on Radio Frequency Deflector by the use of focusing elements", *Sci. Rep.*, vol. 10, p. 11457, Jul. 2020. doi:10.1038/s41598-020-67997-1

[26] L. Sabato, P. Arpaia, A. Gilardi, A. Mostacci, L. Palumbom, and A. Variola, "A Measurement Method Based on RF Deflector for Particle Bunch Longitudinal Parameters in Linear Accelerators", *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1-9, 2021. doi:10.1109/TIM.2020.3009342

[27] C. E. Cocha Toapaxi, "Assessment performance and emittance measurements tests of Basler digital camera vs. the standard BTV system at CLEAR", CERN, Geneva, Switzerland, Rep. CERN-STUDENTS-Note-2019-045, 2019.

[28] M. Gasior, "An inductive pick-up for beam position and current measurements," CERN, Geneva, Switzerland, Rep. CERN-AB-2003-053-BDI, 2003.

[29] S. Doebert, Design of a new e- injector for CLEAR and AWAKE, presented at the 2019 CLIC Workshop, https://indico.cern.ch/event/753671/contributions/3286187/.

[30] J. W. Kovermann *et al.*, "Commissioning of the First Klystron-based X-band Power Source at CERN", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper THPPC060, pp. 3428-3430.

[31] N. Catalán Lasheras *et al.*, "Experience Operating an X-band High-Power Test Stand at CERN", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2288–2290. doi:10.18429/JACoW-IPAC2014-WEPME016

[32] S. Pitman *et al.*, "Connection of 12 GHz High Power RF from the XBOX 1 High Gradient Test Stand to the CLEAR Electron LINAC", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, paper WEPRB063, pp. 2960-2963.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI