ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOST018

THE DESIGN OF A SECOND BEAMLINE FOR THE CLEAR USER FACILITY AT CERN

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Abstract

The CERN Linear Electron Accelerator for Research (CLEAR) has been operating as a general user facility since 2017 providing beams for a wide range of user experiments. However, with its current optical layout, the beams available to users are not able to cover every request. To overcome this, a second experimental beamline has been proposed. In this paper we discuss the potential optics of the new line as well as detailing the hardware required for its construction. Branching from the current beamline, via a dogleg chicane that could be used for bunch compression, the new beamline would provide an additional in-air test stand to be available to users. The beamline before the test stand would utilise large aperture quadrupoles to allow the irradiation of large target areas or strong focusing of beams onto a target. In addition to this there would also be further in-vacuum space to install experiments.

INTRODUCTION

The CLEAR facility provides a flexible electron beam with a wide parameter range to its users [1–4]. The experiments performed at CLEAR have included the irradiation of electronics [5–8], studies into very-high energy electron (VHEE) radiotherapy and FLASH radiotherapy [9, 10], 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].

The beamline undergoes continuous improvement and consolidation [19] to expand the range of available beams, however, some limitations remain. Beams available to users on the in-air test stand have a transverse size between ~ 0.5 - 5.0 mm. The size can be increased by scattering the beam but this produces secondary particles that may be unwanted. The largest beam size is limited by the current optical arrangement of the beamline. Another optics based limitation is placed on the ability to perform strong focusing onto a target in-air. The strong focusing of electron beams is interesting to users working on VHEE radiotherapy and studies performing focusing within a water phantom have previously been done at CLEAR [20, 21]. However, it was only possible to focus the beam in one axis at a time due to the 40 mm diameter beam pipe placing a restriction on the maximum beam size before the final focus. Furthermore, with many proposed experiments and only two in-air test areas, often experimental set-ups have to be dismantled to make space for others, and reinstalled later to carry out further tests.

To improve the range of available beams and increase availability to users a new experimental beamline has been proposed. The new beamline will consist of a simple achromatic dogleg bend followed by an experimental beamline. By using larger aperture quadrupoles the maximum beam size in the new beamline could be expanded allowing the creation of larger beam sizes and the ability to perform increased focusing in both axes. The new beamline will also provide an additional in-air test stand and space for in-vacuum experiments, optimising the availability of testing slots. To reduce the cost of the new beamline, as many components as possible will be taken from the old CTF3 complex [22].

BEAMLINE DESCRIPTION

Table 1: List of Available Quadrupole Magnets

Name	Aperture	$g_{max.}$	Magnetic Length
QL3	40 mm	11.2 T/m	226 mm
QG8	100 mm	8.0 T/m	300 mm
QP	80 mm	12.7 T/m	350 mm
QTN	185 mm	5.33 T/m	385 mm

The present CLEAR beamline consists an RF photoinjector followed by three accelerating structures able to accelerate electron beams, of bunch charges up to 3 nC, to an energy between 60 - 220 MeV. There is an experimental beamline extending 18.4 m from the end of the third accelerating structure. At the end of the beamline there is a 0.9×1.2 m in-air test stand before a dump. There are three quadrupole triplets installed and one doublet, each using narrow aperture QL3 quadrupoles. Two MDX-type dipole magnets are installed on the beamline for use as both spectrometers and to direct the beam onto in-air test stands. One dipole is positioned before the in-air test stand at the end of the beamline. The other dipole is located 3.8 m after the end of the last accelerating structure and is used to direct beams onto the VESPER test stand. Along the beamline there are several diagnostics installed including, beam television screens (BTV) for beam profile measurements, inductive BPMs for beam position measurements, and an RF deflecting cavity to measure the longitudinal phase space of the bunch. The locations of all components installed on the present beamline are fully documented in the CLEAR lattice files [23].

The proposed layout for the new beamline in relation to the existing experimental beamline is shown in Figure 1, and the parameters of the available quadrupole magnets used

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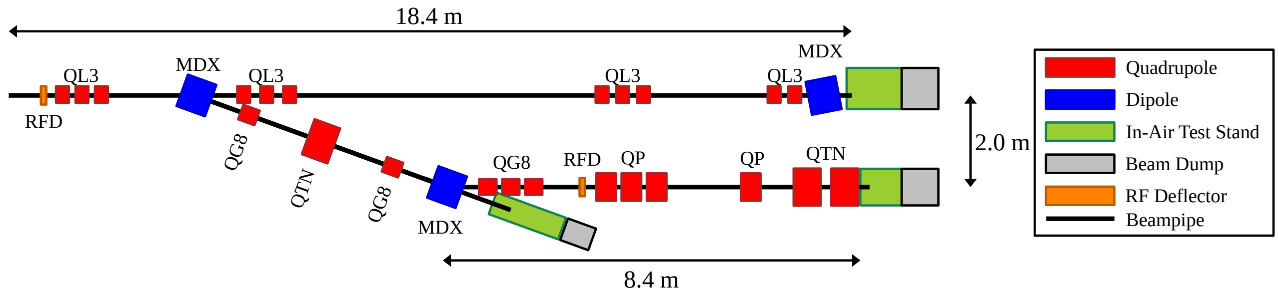

Figure 1: Scale diagram of the current experimental beamline (top) and the proposed second experimental beamline (bottom) beginning at the exit of the final accelerating structure. The magnet types are labelled and the physical dimensions shown.

in the new beamline are listed in Table 1. The beamline branches from the present beamline at the location of the MDX dipole used for the VESPER test stand. It has previously been shown that high-charge bunches could be compressed to sub-ps bunch lengths using the velocity bunching technique [19]. Therefore, the dogleg was optimised to provide the most experimental space whilst not degrading the quality of the beam significantly, and not for bunch compression. The distance between the two beamlines was set to 2 m to allow access to both sides of the new beamline. A bend angle of 20° was selected resulting in an R_{56} of −0.0192 m. Three quadrupoles are positioned on the dogleg to eliminate dispersion. A de-focusing QTN quadrupole is located at the centre of the dogleg, with two focusing QG8 quadrupoles located between the midpoint and each dipole. A BTV screen would be located between the dipole and the first quadrupole to be used as a spectrometer. Two BPMs would be installed on the beamline between the focusing quadrupoles and the central quadrupole to measure the beam trajectory. The three quadrupoles used have apertures large enough to allow a beampipe of 100 mm width to be installed if this is required to reduce losses in the dogleg. However, a beampipe of 40 mm diameter is preferred as it would allow the installation of the inductive BPMs currently used on CLEAR and not new BPMs with larger apertures. There would be space to install an in-air test stand with a length of 1.6 m, similar in size to the present VESPER test stand after the second dipole. The quadrupole magnets installed on the dogleg would allow the beam size and dispersion to be tuned, which is not possible on the VESPER test stand.

Following the second dipole there is the new experimental beamline. The total length of the new beamline is 8.4 m. There are three triplets installed. A QG8 triplet would be installed to control the beam following the dogleg, followed by a triplet of QP quadrupoles and a final triplet of QP and QTN quadrupoles. Between the triplets on the new beamline, there are 1.1 m and 1.6 m spaces for diagnostics and in-vacuum experiments to be installed. At least one BTV screen and BPM should be installed in each drift as well as a final BTV screen following the final quadrupole. An identical RF deflecting cavity could be installed following the QG8 triplet to allow measurements of the longitudinal phase space of the beam following the dogleg. Each magnet used has a larger aperture than the QL3 quadrupoles installed on the existing beamline. In the initial design, a 40 mm diameter beam pipe is considered for most of the new beamline in order to be compatible with existing diagnostics, but there would be a transition to an 80 mm beampipe 300 mm before final triplet followed by a 185 mm beampipe before the final two magnets. At the end of the beamline there is space for an additional in-air test stand to be installed. If the dump is located at the same distance as the present dump then the new test stand could only be 900 mm long. However, it would be possible to move the dump further back to extend both the test stand size and beamline length which should be investigated further.

BEAM DYNAMICS

To investigate the beam dynamics of the new beamline and optimise its layout, a 0.5 nC bunch was simulated to the exit of final accelerating structure using the ASTRA model of CLEAR [24, 25]. The bunch had $\epsilon_{x,n}$ and $\epsilon_{y,n}$ of 8.76 and 8.24 π mm mrad, β_x and β_y of 14.8 and 13.9 m, α_x and α_y of −1.63 and −1.57, a bunch length of 4 ps, and an energy spread of 0.4 %, similar to beams measured experimentally [2]. The bunch was then tracked through the dogleg and experimental lines using RF-Track [26, 27].

Dogleg Bend

The optics of the dogleg are shown in Fig. 2. It is possible to fully suppress dispersion in the dogleg and provide a non-diverging beam with $\beta_{x,y}$ of 20 m to the rest of the experimental line. The maximum dispersion in the dogleg was 0.4 m resulting in a maximum rms beam size of 1.3 mm for a single bunch. If a 40 mm beam pipe is used then it would be possible to transport bunch trains with an energy spread of up to 5 % rms without significant losses corresponding to bunch trains of ∼ 20 nC. If a beam pipe with a 100 mm aperture is used, it would be possible to transport trains of higher charge. There was an increase in bunch length over the dogleg of 0.2 %. By simulating the dogleg in CSRtrack [28] it was shown that coherent synchrotron radiation does not lead to a a significant increase in emittance. It was shown that by adjusting the phase of the RF cavities in the ASTRA model it was possible to perform some bunch compression with the dogleg, however, this must be investigated further.

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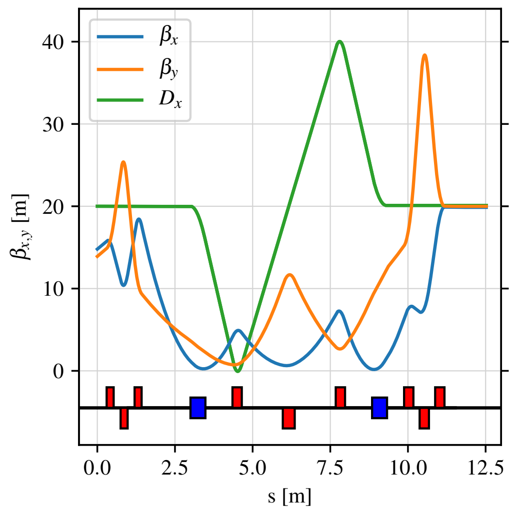

Figure 2: Beam optics of the dogleg bend.

New Experimental Beamline

Following the first triplet the beam was tracked through the rest of the experimental beamline using RF-Track. An optimisation of the strengths of the quadrupoles was performed for two optical arrangements at the in-air test stand, a non-diverging beam of 10 mm rms beam size and strong focusing. The evolution of the beam size when the magnet strengths are optimised to produce a beam size of 10 mm with $\alpha_{x,y} = 0$, is shown in Figure 3. In this optical configuration the maximum beam size is 18 mm in the penultimate QTN. If the proposed aperture is used then there are losses of less than 0.5 %. The beamline could also be configured to

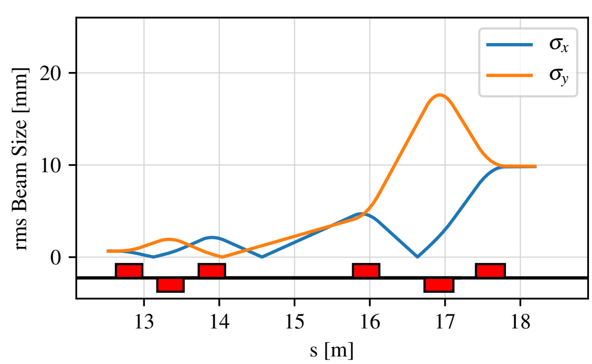

Figure 3: The beam size vs distance along the new beamline with optics configured for a large, non-diverging beam.

allow strong focusing of the beam towards a target. Figure 4 shows the evolution of beam size when the magnet strengths are optimised to provide strong focusing in both axes onto a target located 300 mm from the exit of the final quadrupole. The rms beam size grows to 25 mm, which leads to losses of around 1.5 % in simulation. The effects of scattering with the beam exit window, air, and any medium placed between the exit window and the target, such as a water phantom, have not been considered here and should be investigated further. For this optical arrangement the focusing gradient of

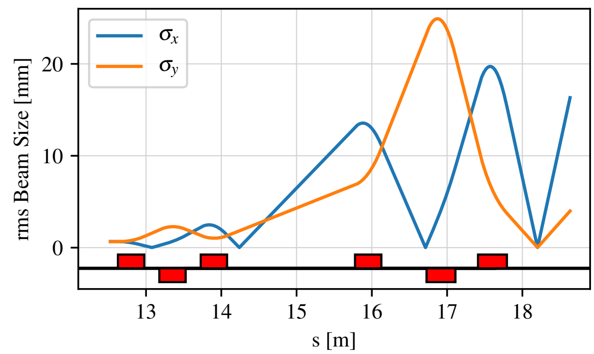

Figure 4: The beam size vs distance along the new beamline with optics configured for strong focusing.

the final QTN quadrupole is required to be 6.22 T/m, higher than the nominal value in Table 1. However, the magnet is able to operate at a current of 250 A, with the nominal field gradient given for current of 150 A. The full excitation curve up to 250 A must, therefore, be measured prior to installation, and the maximum gradient verified.

FURTHER WORK

Prior to commissioning the ability to undertake bunch compression using the beamline should be investigated. Additionally the option to extend the distance of the new dump further than the present dump should be studied balancing the size of the in-air and in-vacuum space. The necessary beam diagnostics and their locations should be defined. The new magnets, currently in storage, should be identified and their condition assessed. Work should also be done to identify the cabling and power supplies needed to power these magnets.

CONCLUSION

The development of CLEAR to increase the range of different beams available to users is a continuous task. A second beamline has been designed which would provide new in-air and in-vacuum experimental space. Furthermore, the design of the new beamline would allow the creation of beams with larger beam sizes to be produced, and strong focusing to be performed.

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