DISPERSION FREE AND DISPERSION TARGET STEERING EXPERIENCE AT CTF3

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Abstract

One of the goals of the CLIC Test Facility (CTF3) [1] at CERN is to demonstrate the feasibility of the CLIC [2] Drive Beam recombination, which takes place in the Drive Beam Recombination Complex (DBRC). The tight geometry of the DBRC together with its strong optics and the high energy spread of the beam require a careful control of the beam size along the different sections of the DBRC [3, 4]. One of the main contribution to beam size is the dispersion. If uncontrolled, dispersion leads to fast increase of the beam size, hence it may affect the beam current stability of the combined beam. A tool has been implemented at CTF3 to measure and correct dispersion during and after the setup of the machine. Dispersion Free Steering (DFS) has been applied in the upstream Drive Beam LINAC, while Dispersion Target Steering (DTS) has been used in the rings of the DBRC. In the LINAC the weak optics and the wide dynamic aperture of the beamline allow a straightforward correction. In the DBRC the aperture is tighter, and the strong optics produce non-linear dispersion which one needs to take into account. A general overview of current status and future plans in controlling dispersion at CTF3 will be presented.

INTRODUCTION

The ability of controlling dispersion is part of a broader topic, which is the necessity of preserving the beam quality while transporting it over long distances [5]. One of the main sources of beam quality degradation is connected to orbit errors which normally translates in undesired dispersion and emittance dilution.

Dispersion can be used as a convenient observable for steering the beam by means of the DFS technique [6]. DFS is currently one of the main tools for minimising the emittance growth in the CLIC main beam [7]. Experimental verification of DFS were successfully performed at SLAC [8].

One of the main objective of the CLIC Test Facility (CTF3) program [1] is to preserve the emittance of the beam while being recombined in the DBRC. The ability of measuring and controlling the dispersion turned out to be an extremely powerful tool for the set-up and optimisation of the different beam lines.

The layout of CTF3 is shown in Figure 1. Note that the DBRC is composed of a Delay Loop (DL), a Combiner Ring (CR) and connecting transfer lines where clearly dispersion is non-zero by design. Dispersion Target Steering (DTS) is then the natural evolution of DFS to be applied in the DBRC.

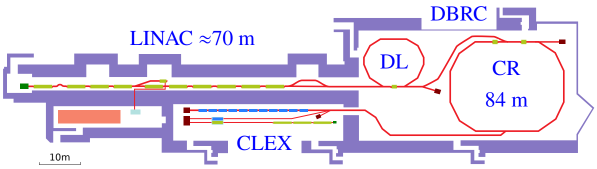

Figure 1: Layout of CTF3 at CERN.

In the following we will give a brief overview of the dispersion measurement tool implemented at CTF3 and its use for DFS, DTS and for machine set-up.

DISPERSION MEASUREMENT

The dispersion in a transfer line can be measured by changing the momentum of the beam with respect to the nominal momentum (p_0) the line is tuned for, and then measuring the mean orbit deviation. The observed orbit displacement (Δx) can be expressed as:

$$\Delta x = D_x \frac{\Delta p}{p_0} + DD_x \left(\frac{\Delta p}{p_0}\right)^2 + o\left(\left(\frac{\Delta p}{p_0}\right)^3\right). \quad (1)$$

One can then fit the coefficients D_x, which is the linear dispersion, and if necessary also the higher order terms (e.g. DD_x). Practically the measurement of D_x is often sufficient to spot errors or mismatches in a beam line.

In transfer lines where dispersion is expected by design another interesting observable is what we call the "nominal" linear dispersion, i.e. the orbit response while scaling *only* the bending magnets. This quantity is not affected by quadrupole misalignments and orbit errors, hence it is a direct measurement, with opposite sign, of D_x in Eq. (1) for the ideally aligned linear machine [4]. Note that the measured quantity is *not* the actual dispersion experienced by the beam, but it is the dispersion contribution of the bending magnets which, in an ideal-linear machine, are the only sources of dispersion. This observable turns out to be useful for optics verification and it can be used to define the target dispersion for DTS.

At CTF3 a MATLAB application to perform online measurements of linear and non-linear dispersion has been developed [4]. The relative energy of the beam with respect to the beam lines can be varied mainly in three ways:

- By scaling all the magnetic elements in the line. Note that this method would not reveal the *incoming* dispersion, but only the dispersion generated within the section of beam line being scaled.

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- By scaling the beam current delivered by the thermionic gun. Since the Drive Beam linac relies on fully loaded accelerating structures, one can assume a linear correlation between beam current and beam acceleration [1].

- By varying the phase and/or power of the accelerating structures in the linac, which has a similar effect as scaling the beam current.

The more convenient method is to vary the beam current.

DISPERSION CORRECTION

A generic tool for optimising linear and quasi-linear systems at CTF3 was implemented at CTF3 and first used for orbit correction [9]. Thanks to the generality of the implementation the same tool has been used for various optimisations [4], including dispersion correction.

Figure 2 shows the result of applying DFS in the CTF3 linac. The correction was performed by first *measuring* directly on the machine the response matrix of all dipole correctors in the linac. Note the reduction in spurious dispersion below 5 mm. At the same time a similar correction was performed in the vertical plane reducing the vertical dispersion from about 10 mm to less than 1 mm [4]. The effect of those corrections was extremely beneficial for the final beam quality. Table 1 shows the Twiss parameters of the beam measured at the end of the linac before and after DFS in the two planes. It is remarkable that the observed emittance was reduced by more than 15 % in both planes, which is proof of the effectiveness of DFS[1].

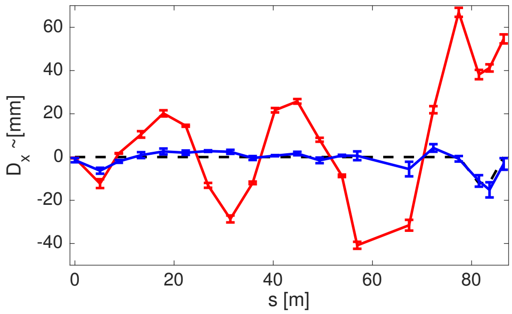

Figure 2: Horizontal dispersion along the linac at CTF3. Black is the design dispersion. Red and blue are the actual dispersions measured by changing the beam energy before and after DFS respectively.

DFS was performed also in the DBRC, but clearly only in the vertical plane where no dispersion is expected by design. In the horizontal plane, where dispersion is non-zero by design in most location, DTS has been tested. Note that for DTS one needs first to know the target dispersion. Naively one could try to target the design dispersion, however any BPM calibration issue or a wrong set up of the quadrupoles strength would drive the correction to an undesired state. Here the concept of "nominal" dispersion previously introduced becomes extremely useful.

Figure 3 shows the result of a DTS attempt in the CR at CTF3. Note the discrepancy at $s \approx 67$ m between the design dispersion (black) and the measured "nominal" dispersion (green) due to a mis-calibration of a BPM. It is clear that if one would target the design dispersion at this location one would have driven the line toward an undesired set-up. For this correction only dipole correctors inside the CR were used, therefore in the first part of the ring DTS does not have enough degrees of freedom, but the correction starts to be effective in the second half of the ring.

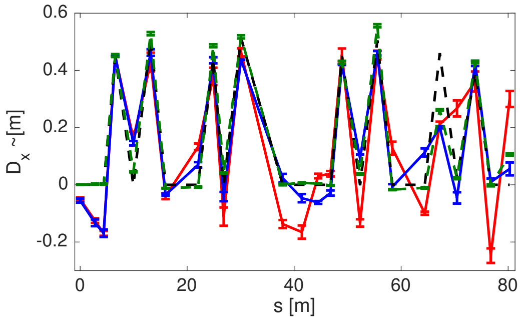

Figure 3: Horizontal dispersion along the CR at CTF3. Black is the design dispersion. Green is the "nominal" dispersion measured by scaling the bending magnets of the ring, and it was used as target for DTS. Red and blue are the actual dispersions measured by changing the beam energy before and after DTS respectively.

DTS is a promising technique, but further experimental verification are needed to prove its effectiveness in improving the Drive Beam recombination quality.

DISPERSION FOR MACHINE SET UP AND OPTIMISATION

One of the recent improvements of the recombination process at CTF3 was the optimisation of the DL optics in order to reduce the outgoing non-linear dispersion [3]. The ability of measuring non-linear dispersion turned out to be useful as a verification of the improvement. Figure 4 shows a scatter plot of consecutive beam shots with different energies at the first BPM after DL for the two different optics. The second order dispersion is clearly visible for both DL optics, but the effect is sensibly reduced for the new one (blue).

Another important use of the dispersion as indicator of the quality of set-up is the use of the "nominal" dispersion measurement previously introduced. Since such a measurement is not affected by misalignments, it gives a direct measurement of the correctness of the quadrupole and relative dipole strengths. Figure 5 shows one of these measurements in the first arc of the CR. Note that in the middle of the arc one expects a dispersion close to zero, while the initial measurement (red) was measuring a "nominal" dispersion sensibly different from zero. By scaling up the quadrupoles in the arc the pattern got closer to the design (e.g. green). The

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[1] The asymmetry between the horizontal and vertical emittances was probably due to errors at the source, lately corrected by other means.

Table 1: Transverse Twiss Parameters of the Beam. Measured at the end of the Drive Beam linac at CTF3 before and after DFS in the linac. Also shown are the nominal Twiss parameters for the ideal machine.

	β_x [m]	α_x	ϵ_{Nx} [μm]	β_y [m]	α_y	ϵ_{Ny} [μm]
Nominal Twiss	8.4	-0.8	–	13.5	-0.4	–
Before DFS	9.2 ± 0.4	-0.7 ± 0.1	**63 ± 1**	11.3 ± 1.2	-0.1 ± 0.1	**129 ± 8**
After DFS	8.7 ± 0.4	-0.5 ± 0.1	**52 ± 1**	10.3 ± 1.0	-0.1 ± 0.1	**102 ± 5**

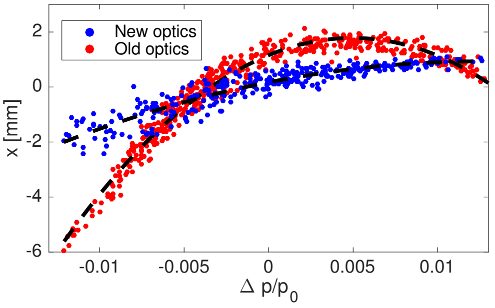

Figure 4: Comparison of non-linear dispersion at the first BPM after the DL for two different DL optics. Scatter plot of the mean position recorded at the BPM versus beam energy variation.

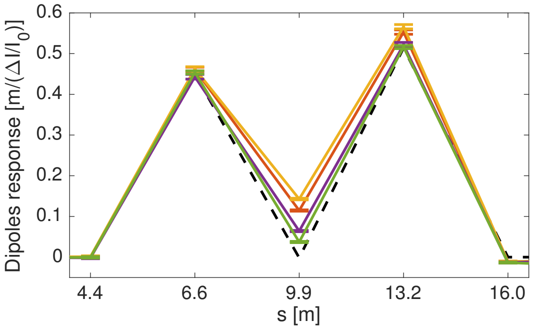

Figure 5: Orbit response at the BPMs in the first arc of CR while scaling the ring dipoles. Black is the design dispersion. Coloured are actual measurements: the initial status (red) and scaling the arc quadrupoles by -1% (yellow), +2% (purple), +3%(green).

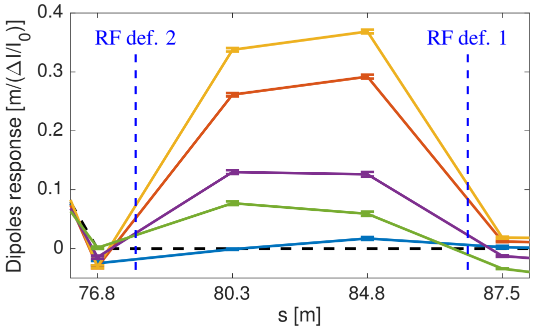

Figure 6: Orbit response at the BPMs around the RF deflectors of the CR while scaling the ring dipoles for the same set-ups of Figure 5. The additional blue measurement was performed with the initial quadrupole strengths but without RF into the deflectors.

improvement could be seen also observing the variation of the ring R_{56}. As one expects to measure the nominal D_x while scaling the bending magnets, then one should be able to reveal at the same time the “nominal” R_{56}. The optics of the CR is meant to be isochronous [1]. For the purpose of beam recombination two RF deflectors are installed around the CR injection. After one turn in the ring the beam is expected to cross the deflectors on zero-crossing. Clearly if R_{56} is non-zero, any variation of path length while scaling the bending magnets results in a visible bump in the orbit, which is seen by the dispersion monitor application as actual “nominal” dispersion. Figure 6 shows this effect during the optimisation of the arc quadrupole strengths presented in Figure 5. Note that also in terms of R_{56} by scaling up the arc quadrupoles the optics got closer to nominal. As a proof that the effect was really given by the lengthening of the beam path, note that when RF was removed from the deflector the effect disappeared (see blue curve in Figure 6).

From Figure 6 one can be more quantitative: the orbit excursion expected with the RF bump can be written as:

$$\Delta x \approx R_{56} \frac{\Delta p}{p_0} \frac{2\pi}{\lambda_{RF}} x_{max} \,, \qquad (2)$$

where λ_{RF} is the RF wavelength and x_{max} is the maximum orbit excursion expected when the beam is crossing the cavities on crest. By scaling the bending magnets one actually measures the overall linear coefficient of Eq. (2) with respect to $\Delta p/p_0$. By knowing that $x_{max} \approx 25$ mm; $\lambda_{RF} \approx 10$ cm one can than estimate $R_{56} \approx 0.16$ m before the correction (red) and $R_{56} \approx 0.04$ m after the correction (green).

CONCLUSIONS

The ability of measuring and controlling dispersion in the different beam lines has been demonstrated. A series of examples has proven the potential of using dispersion not only for beam steering (DFS and DTS), but also as a mean for optics optimisation. Currently these kind of measurement and optimisations are the basis for the completion of the experimental programme of CTF3 [10].

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