NULLING EMITTANCE MEASUREMENT TECHNIQUE FOR CLIC TEST FACILITY

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Abstract

In order to test the principle of Two-Beam-Acceleration (TBA), the CLIC Test Facility utilizes a high-intensity drive beam of 640 to 1000 nC to generate 30 GHz accelerating fields. To ensure that the beam is transported efficiently, a robust measurement of beam emittance and Twiss parameters is required. This is accomplished by measuring the beam size on a profile monitor, while scanning five or more upstream quadrupoles in such a fashion that the Twiss parameters at the profile monitor remain constant while the phase advance through the beam line changes. In this way the beam size can be sampled at different phases while a near-constant size is maintained at the profile monitor. This eases many of the difficulties of such measurement devices, especially those associated with limited dynamic range. In addition, the beam size is explicitly constant for a matched beam, which provides a "nulling" measurement of the match. Details of the technique, simulations, and results of the measurements are discussed.

1 INTRODUCTION

The CLIC Test Facility (CTF) was constructed in order to demonstrate the validity of the two-beam acceleration (TBA) scheme proposed for CLIC, and to gain real-world experience with such a scheme in an accelerator environment. The CTF consists of a pair of linacs constructed side by side: a Drive Beam, which accelerates a high charge electron beam to roughly 50 MeV and injects same in to a line of 30 GHz CLIC Transfer Structures (CTS); and a Probe Beam which accelerates a low charge to roughly 40 MeV and injects same into a line of 30 GHz CLIC Accelerating Structures (CAS). Energy is removed from the Drive Beam via the CTS and transferred to the CAS. The final energy of the Probe Beam after acceleration in the CAS is expected to be 320 MeV [1].

In order to generate the required accelerating fields in the Probe Beam, the Drive Beam will consist of 48 bunches of 14-21 nC, for a total charge on each RF pulse of up to 1 μC [2]. Such high charges imply serious issues of wakefields, beam loading, and beam size, especially since the beam is required to pass through the CTS region in which the aperture is 15 mm diameter. In order to pass through such small apertures, the normalized rms emittance of the Drive Beam train cannot exceed 200 mm.mrad, corresponding to a limit of 1000 mm.mrad for the entire beam [3].

In order to ensure that such tolerances are met, it is necessary to have some means of measuring the emittance of the Drive Beam, which can then be used to tune charge, orbits, RF phases, for example, until the limits above are met.

In an accelerator of the sort described above, the traditional method of emittance measurement is the so-called "quad scan" technique: the beam is focused to a waist on a profile monitor, and the beam size at the monitor is measured as a function of the strength of an upstream quadrupole. This allows reconstruction of the beam phase space at the upstream face of the scanned quadrupole [4]. In the case of the CTF Drive Beam line, such an arrangement is not optimal for several reasons. First, the small aperture of the CTS mandates that all waist points in the beamline be reserved for RF cavities, not profile monitors, and the waists are difficult to shift. Second, the dynamic range demanded by the quad scan technique is difficult to achieve: because the beam size must be modulated by a factor of $\sqrt{2}$ for good resolution of the parameters, quad scans tend to have poor signal-to-noise performance when the beam is large (at the scan extremes), and saturation when the beam is small (at the center of the scan). Third, the profile monitor of choice in the CTF is a combination Transition/Cerenkov Monitor (TCM): an extremely small beam with the high charge and energy parameters described above is likely to damage the TCM. For these reasons a traditional quad scan was contraindicated, and a different technique had to be devised.

2 NULLING EMITTANCE TECHNIQUE

The principal requirement of an emittance measurement technique is that the beam size be measured at different betatron phases, to allow reconstruction of the beam matrix at a single point. Consequently it is possible to imagine a technique in which only the betatron phase is varied, and the beam parameters at the profile monitor remain constant.

This is the basis of the measurement method used on the CTF Drive Beam. Given the design Twiss parameters at a "treaty point" in the line (β_0, α_0), the design parameters at a downstream profile monitor (β_f, α_f), and the design phase advance ν, the strengths of the intervening quads are varied such as to alter the phase advance but still result in the same final beam parameters.

If the beam is not perfectly matched at the treaty point, some modulation of the beam size will occur during the scan; for a perfectly matched beam, no modulation will occur (as opposed to a quad scan, in which modulation occurs under all beam conditions). Thus, for a reasonably-well matched beam, the adjustment of profile digitization and filtering remains valid over the entire scan range, and a

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large beam size can be maintained on the profile monitor at all times. The technique can be thought of as "nulling" in that a perfectly matched beam experiences no modulation in the measured size, and thus the technique has maximum sensitivity when the tunable parameter (mismatch) is near its minimum.

2.1 Calculation of Quadrupole Strengths

In this measurement, there are four parameters which are held constant – β_x, β_y, α_x, and α_y – while one parameter is varied, specifically the betatron tune in the measurement plane (the tune in the non-measured plane was not constrained). This requires 5 quadrupole magnets in all. In the CTF Drive beam, six magnets (arranged in 2 triplets) were varied for emittance measurements, and the extra degree of freedom allowed greater scanning ranges. The quad strengths for each scan were generated by the lattice-fitting facility of DIMAD [5], since the quad strengths vary nonlinearly as a function of tune, as shown in Figure 1. The total range of betatron phase allowed by quad strength limitations was 108° in the horizontal and 72° in the vertical.

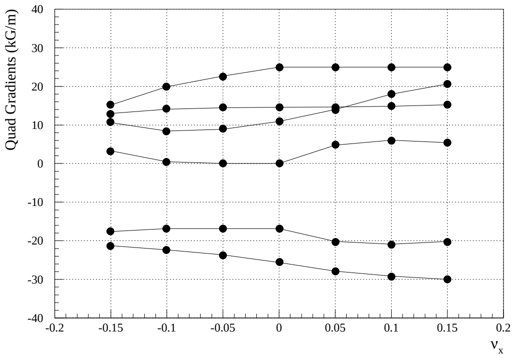

Figure 1: Quadrupole strengths required for ν_x scan.

2.2 Calculation of the Beam Matrix

Calculation of the incoming beam matrix follows the traditional emittance measurement formalism. Given an incoming sigma matrix $\sigma^{(0)}$ and a sigma matrix at the profile monitor $\sigma^{(p)}$, the relationship between $\sigma_{11}^{(p)} \equiv (\sigma_x^{(p)})^2$ and $\sigma^{(0)}$ is:

$$\begin{aligned} \sigma_{11}^{(p)} &= R_{11}^2 \sigma_{11}^{(0)} + 2R_{11}R_{12}\sigma_{12}^{(0)} + R_{12}^2\sigma_{22}^{(0)} \qquad (1) \\ &= r_1 s_1 + r_2 s_2 + r_3 s_3, \end{aligned}$$

where we have defined shorthand variables r_j and s_j to denote transport and beam terms, respectively, of Equation 1. At each step of the scan the beam size is measured and $\sigma_{11}^{(p)}$ calculated; the R matrix from the input to the screen is calculated from the quad strengths. A least-squares solution to Equation 1 satisfies the matrix equation

$$a = Bc, \qquad \text{where} \qquad (2)$$

$$\begin{aligned} a_j &= \sum_i \frac{r_j(i)\sigma_{11}^{(p)}(i)}{\delta^2(i)}, \\ B_{jk} &= \sum_i \frac{r_j(i) r_k(i)}{\delta^2(i)}, \\ c_k &= s_k, \end{aligned}$$

where (i) denotes the values on the ith step of the measurement and $\delta(i)$ is the measurement error on $\sigma_{11}^{(p)}(i)$. The matrix in Equation 2, a 3 x 3 symmetric matrix, can easily be inverted analytically to yield a solution for the terms of $\sigma^{(0)}$.

2.3 Simulation of Emittance Scans

Emittance scans were simulated using DIMAD to track 1000 particles through each step of the emittance scan. Because DIMAD's tracking engine is second-order, this allowed examination of distortions to the fit arising from chromaticity in the quadrupoles between the treaty point and the profile monitor. Table 1 shows the results of the simulation, with monochromatic beam parameters, beam parameters from the sigma matrix of the tracked particles (1% rms energy spread) at the end of the line, and fitted parameters (assuming 10% resolution of the profile sizes). Note that the distortions due to chromaticity are small (deviations of second column from first column), and fitted values agree within errors.

Table 1: Results of simulation studies of Nulling Emittance Technique.

Parameter (unit)	1st Order value	2nd Order value	Fitted value
$\gamma\epsilon_x$ (mm.mrad)	18.4	18.4	18.1 ± 1.4
β_x (m)	0.945	0.986	1.01 ± 0.09
α_x	-1.129	-1.186	-1.19 ± 0.13
$\gamma\epsilon_y$ (mm.mrad)	18.4	19.0	19.4 ± 3.0
β_y (m)	2.691	3.045	3.06 ± 0.6
α_y	-0.600	-0.699	-0.72 ± 0.27

3 RESULTS OF EMITTANCE MEASUREMENT

Early tests of the nulling emittance measurement technique resulted in poor fits and, frequently, imaginary emittances in the vertical plane. Further investigation revealed that both of these pathologies were improved by reducing the strength of the final quadrupole in the fits by roughly 20% at all magnet currents. It was subsequently discovered that the final quad was in fact of a different design from the others, and was weaker than other CTF quads by design. Because the final quad's current-vs.-gradient performance was uncertain, the scans were redesigned to leave the final quad at zero field (its design strength in the 1996 CTF optics).

Another pathology observed in early tests was that at certain points in the scan the beam size would increase to fill the profile monitor, while for most of the points the beam size varied smoothly. Upon examination it was seen that the scan region which produced well-behaved spot sizes was the region in which all quad strengths were varied monotonically and by increments small compared to their overall strengths, the so-called "perturbative" region of the scans. Magnet scans were re-configured to use only the perturbative regions, resulting in a reduction in the total phase shift available. However, the S/N performance of the system (determined by repeating the scan 3 times and forming an average and rms of the 3 measurements at each point) was seen to be better than expected, and thus the reduction in phase shift did not compromise the fit quality unacceptably. The cause of the discontinuous beam size behavior is not known.

A final oddity observed was that consecutive measurements of the beam emittance would result in inconsistent fits, while the data appeared to be qualitatively similar from one fit to the next. It was determined that on each fit, one point (consisting of 3 beam sizes averaged together) would have a much smaller variance than the other points (as little as 1 μm, while all other points were closer to 20 μm). Because a different point in each scan would be anomalous in this fashion, the low-variance points would pull the fits out of agreement. This was corrected by adding an error of 10 μm in quadrature with the measured variance. This would preserve the overall relative weighting of points but prevent the fits from being pulled in the fashion described. Figure 2 shows a horizontal emittance scan, with the measured data (points) and fit (lines) superimposed.

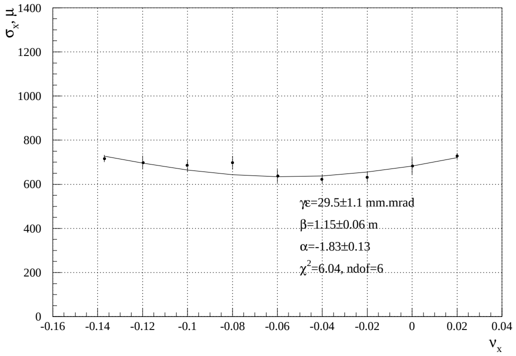

Figure 2: Example of emittance measurement in CTF.

Using the measurement technique as described above, the CTF Drive Beam single- bunch emittance was measured at different bunch charges (2 to 4 nC) and source laser spot sizes (0.7 to 2 mm diameter). Normalized emittances varied from 30 to 50 mm.mrad in the horizontal, and 35 to 70 mm.mrad in the vertical.

4 SYSTEMATIC ERRORS

There are several possible sources of systematic error which can affect the emittance measurement:

- A profile monitor scale factor of up to 2%, based on pixel calibration asymmetries
- A 5% error in determination of absolute energy, based on comparing 2 methods of measurement
- magnet scale factors up to 1% and offsets up to 1% of maximum strength.

The first two errors were studied analytically, while magnet errors were studied via a Monte Carlo simulation. The results of these studies are summarized in Table 2, and compared to systematic errors.

Table 2: Relative contributions of statistical and systematic errors.

Name	Value (typ.)	Stat. error	Scale error	Energy error	Magnet error
$\gamma\epsilon_x$	30-50	5-7 %	4%	25%	10%
β_x	1.4	5-7 %	0%	5-7%	2-3%
α_x	-1.5	0.2	0.0	0.15	0.03
$\gamma\epsilon_y$	36-70	10-15%	4%	25%	15%
β_y	2.5	10-15%	0%	10-15%	10-15%
α_y	-1.0	0.3	0.0	0.2	0.15

5 CONCLUSIONS

The Nulling Emittance measurement technique is a viable method for measuring beam parameters in environments where the standard quad scan is not available. In the CTF Drive Beam, good statistical resolutions have been achieved for all beam parameters. Some systematic errors (particularly beam energy error) require improvement.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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