Drive Beam Phase Measurement using RF data from the PETS

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Abstract

We briefly describe how we can determine the phase, or equivalently the arrival time of individual bunches of the drive beam in the two-beam test stand using the directional couplers in the PETS recirculation data. The method works independently of the setting of the power splitter in the recirculation loop, including the configuration with recirculation turned off.

The two-beam acceleration scheme for CLIC is presently tested in the CLIC test facility 3 (CTF3) at CERN, where a high intensity drive beam with a suitably chosen time-structure is passed through so-called power extraction and transfer structures (PETS) in order to generate the microwaves to accelerate a low-intensity main beam to high energies. The power generation process in the PETS crucially depends on the properties of the drive beam, in particular through the bunch length which influences the form factor that is responsible for the coupling of the drive beam to the radio-frequency field and the spacing between successive bunches, or, equivalently, the phase of the arriving bunch train. The latter quantity is of crucial importance for beam stability in the accelerated main beam, because it determines whether bunches of the main beam are accelerated on-crest or off-crest, which leads to an increased energy spread and subsequently to an increased emittance.

For this reason the phase of the drive beam and its coupling to the RF field are relevant quantities to determine experimentally. The quantities are for example influenced by the energy profile of the pulse train and the correlation between energy and arrival time (R_{56} in MAD notation) between the point where the energy variation of the macro pulse is imprinted and the PETS structures. Their origin can therefore lie in the delay loop, combiner ring and the TL2 beam line. We assume that it also makes sense to correct such variations by, for example, tuning the phases in the drive beam linac or R_{56} in TL2. The latter beam line is actually designed to provide bunch compression to shorten the bunch after the combiner ring, where it was deliberately lengthened to reduce the peak current and thereby alleviate instabilities. The tuning requires of course a signal to observe and optimize, which is the subject of this note.

It should be noted that the described phase variation of the 12 GHz X-band phase corresponds to minute temporal variations, because 1 degree of X-band phase is equivalent to 230 fs or a quarter of a ps. In the algorithm described below we will determine the sought quantities from the RF signals in the PETS recirculation loop. The method is based on standard linear algebra methods and also provides an estimate of the precision in the determination of the quantities.

We start by considering the field in the PETS structure that is driven by the beam current of the drive beam. With recirculation of the field, the field at time step m, which we denote by E_m depends on the beam intensity I_m at the same time and the field in the structure one recirculation time before, which we denote by time E_{m-1}. Thus we can write

$$E_m = qE_{m-1} + ce^{i\alpha_m} I_m \tag{1}$$

where we introduce the coupling constant to the beam c and the arrival phase variation of the beam $e^{i\alpha_m}$. Moreover, we denote the round trip gain g and phase ϕ of the recirculation loop by $q = g\,e^{i\phi}$. Note that the electric field E_m is a complex quantity that is given in terms of in-phase signal often denoted by I (not to confuse with the beam current which is denoted by the same symbol) and quadrature signal Q. Furthermore, we do not measure the field in the PETS, but the field $\bar{E}_m$ somewhere in the system, but outside the PETS. We therefore have the following relationship between the measured complex field $\bar{E}_m$ and the field in the PETS E_m

$$\bar{E}_m = e^{i\psi} E_m \ . \tag{2}$$

Inserting in eq. 1 we find

$$\bar{E}_m = q\bar{E}_{m-1} + c\,e^{i(\alpha_m+\psi)} I_m = q\bar{E}_{m-1} + r_m I_m \ . \tag{3}$$

Here we observe that the complex recirculation parameter $q = g\,e^{i\phi}$ and the coupling coefficient to the beam $r_m = c\,e^{i(\alpha_m+\psi)}$ are unknown. Observe that we cannot disentangle the absolute value of the arrival phase α_m and the phase ψ between the PETS and the point where we observe the field $\bar{E}_m$. This is just a manifestation that absolute phases cannot be measured, only relative phases have physical significance. Note also, that additional attenuation between the PETS and the observation point will cause the phase ψ to acquire an imaginary value. This would be equivalent to a modified coupling constant to the beam c. We therefore cannot disentangle attenuation between PETS and observation point and coupling constant.

We now need to proceed and solve eq. 3 for the complex coupling g and the coefficients r_m. We observe that eq. 3 is linear in the sought quantities and we can therefore employ linear algebra to that. The equation 3 was somewhat sloppily written and the time step was tacitly assumed to be the recirculation time. In general that is, however, not the case. Moreover the BPM signal with the current I_m is sampled at a different rate than the RF signals $\bar{E}_m$. Furthermore, there are unknown cable lengths to account for to guarantee that the time axes of the different signals coincide. There are different ways of doing that and one way is described in reference [1] and [2]. We suggest to use the sampling time of the RF signals which typically is 1 ns. Once the temporal alignment of the different signals is done we note that we can rewrite eq. 3 in the following way

$$\bar{E}_m = q\bar{E}_{m-n} + c\, e^{i(\alpha_m+\psi)} I_m = q\bar{E}_{m-n} + r_m I_m \;. \tag{4}$$

where we replaced $m-1$ in the subscript of the electric field by $m-n$ where n corresponds to the recirculation time in ns. From this equation we can now determine the round trip gain g and the coupling r_m that includes the arrival phase α_m.

For this exercise we initially assume that the beam coupling coefficients r_m are constant and equal to an average value $\bar{r}$. The equations can then be written in the following way

$$\begin{pmatrix} \vdots \\ \bar{E}_m \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots & \vdots \\ \bar{E}_{m-n} & I_m \\ \vdots & \vdots \end{pmatrix} \begin{pmatrix} q \\ \bar{r} \end{pmatrix} \tag{5}$$

where the left hand side vector is the column vector of the complex electric field and the first column of the matrix is the same vector shifted down by n entries. the second column is the column vector of the BPM signal. Equation 5 is a vastly overdetermined linear system of equations with two unknowns q and $\bar{r}$ that can be solved in the least-squares sense in the usual way

$$\begin{pmatrix} q \\ \bar{r} \end{pmatrix} = \left(A^*A\right)^{-1} A^* \begin{pmatrix} \vdots \\ \bar{E}_m \\ \vdots \end{pmatrix} \tag{6}$$

where A is the matrix in eq. 5 and A^* its hermitian conjugate. It is useful to note that $\left(A^*A\right)^{-1}$ is the covariance matrix [3] that can be used to estimate the error bars of the fitted parameters. Here we are mainly interested in the complex recirculation gain g which can be estimated very accurately in this way which was the subject of ref. [4]. We note that the average phase along the bunch should vary around zero and that the average along the bunch can therefore be attributed to the phase ψ between the PETS and the observation point.

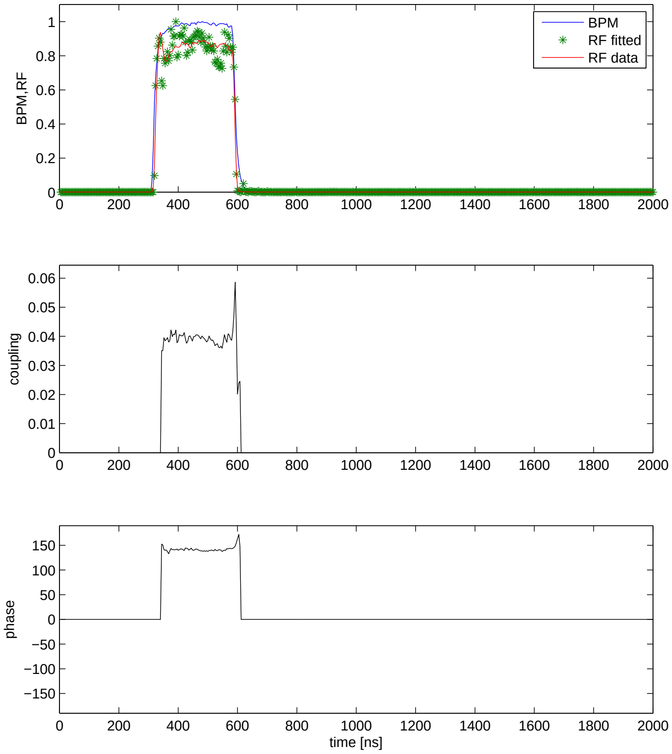

Figure 1: The results of the analysis for one event. The top plot shows the BPM pulse in blue and the measured and fitted RF pulse in green and red, respectively. The middle plot shows the coupling abs(r) between beam and RF and the lower plot shows the phase along the pulse.

In a somewhat weird twist of argument we now continue and assume that q is given by the value we just determined, but that from now on the r_m are variable again and can be determined from solving eq. 4 for r_m

$$r_m = \frac{\bar{E}_m - q\bar{E}_{m-n}}{I_m} \; . \tag{7}$$

The coupling to the beam is given by the modulus of r_m and should be rather constant and the argument (phase) of r_m is the sought drive beam phase. Any variation of the modulus could be interpreted as a variation of the magnitude of the coupling, for example due to varying bunch length that affects the form factor. Alternatively we can also try to use the modulus from $\bar{r}$ and just determine the phase.

We apply the analysis to data collected by the conditioning software [5]. For

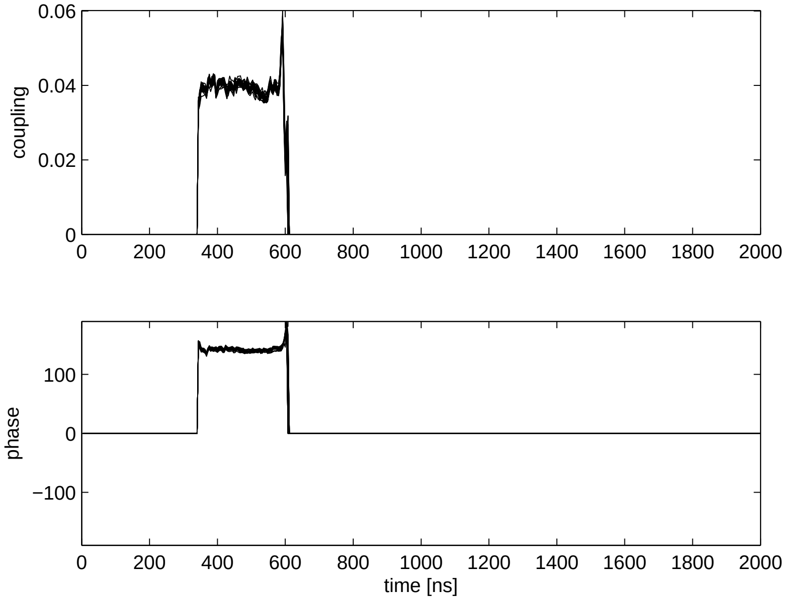

Figure 2: The derived coupling and phase superimposed for 23 events taken in close succession.

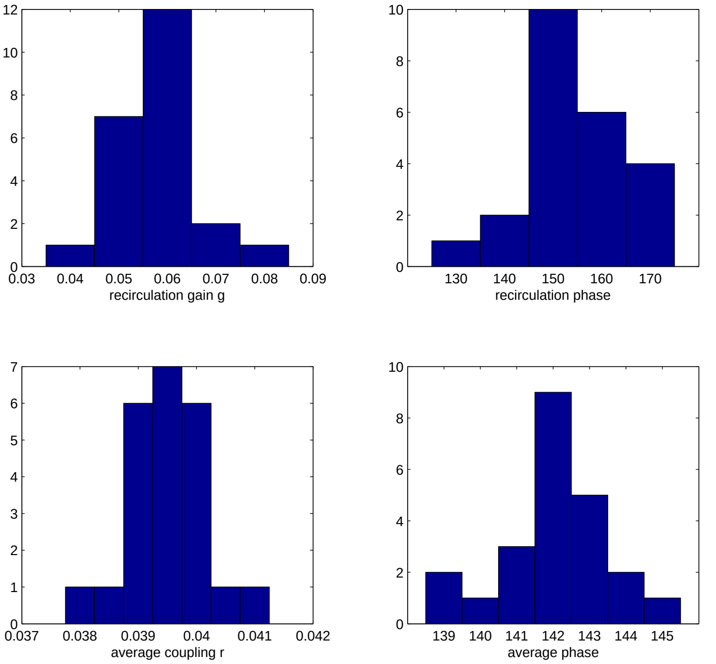

Figure 3: The histograms of the recirculation gain and phase in the top row and the average coupling and phase in the bottom row for the same 23 events.

these test the recirculation was deliberately set to a low value in order to reduce the power level in the PETS and thereby reduce the probability of breakdown. We then collected a sequence of pulses one after the other. The data set used here contains 23 pulses. Applying the analysis to one specific pulse we obtain the results shown in Fig. 1. The top plot shows the BPM trace in blue and the measured (green) and fitted (red) RF trace after the BPM pulse and RF data are aligned using the method from Ref. [2]. We find that the measured and fitted RF pulse are tracking one another nicely. The center plot in Fig. 1 shows the variation of the coupling between beam and RF abs(r) along the pulse train and the bottom plot shows the phase variation along the pulse train. In the analysis we only plot data at points where there is either BPM or RF signal present in order to avoid distracting noise in regions of no interest. We note that the average recirculation gain and phase in this case were found to be 0.058 and 148 degrees. The average coupling to the beam was determined to be 0.039 and the arrival phase to be 141 degree. At the moment we can offer no explanation for the particular variation along the pulse that is shown in Fig. 1, especially the spike near the end of the pulse is somewhat puzzling.

In order to see by how much the coupling and phases vary from pulse to pulse and how stable features in the time variation are reproducible from pulse to pulse we repeated the same analysis that led to Fig. 1 for the entire data set of the 23 saved events and display the result in Fig. 2. In the upper plot we display the 23 traces superimposed and find that they track each other rather accurately. The same is true for the phase shown on the lower plot in Fig. 2. We interpret this in a way that the observed variation actually represents a physical feature of the system and not just an artefact of the method.

It is instructive to determine by how much the average parameters for recirculation gain and phase as well as the average coupling and phase vary from event to event. We therfore display histograms of these parameters for the 23 events in Fig.3. We find that the recirculation gain, which is shown in the top left corner, can be determined to the level of 0.01, that is percent level. The recirculation phase, shown in the top right, is somewhat worse determined to be within 10 degrees, likely due to the fact that the recirculation was very low. The average coupling to the beam which is proportional to the beam current and form factor varies on the 10^{-3} level as is visible on the bottom left plot in Fig. 3 and the average phase is varying on the few degree level.

We conclude that the presented method to determine the variation of the coupling between beam and RF in the PETS and the arrival phase of the beam can be determined to the level of percent and degree, respectively. The algorithm is very simple and quick to implement and we hope that it can be used as a crosscheck for other methods.

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