DESIGN OF PHASE FEED FORWARD SYSTEM IN CTF3 AND PERFORMANCE OF FAST BEAM PHASE MONITORS *

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Abstract

The CLIC two beam acceleration technology requires a drive beam phase stability better than 0.3 deg rms at 12 GHz, corresponding to a timing stability below 50 fs rms. For this reason the CLIC design includes a phase stabilization feed-forward system. It relies on precise beam phase measurements and their subsequent correction in a chicane with the help of fast kickers. A prototype of such a system is being installed in the CLIC Test Facility CTF3. In this paper its design and implementation is described in detail. Additionally, the performance of the precision phase monitor prototypes installed at the end of the CTF3 linac, as measured with the drive beam, is presented.

DESIGN

The layout of CTF3, the CLIC test facility at CERN[1], is shown in Figure 1. In May 2013 installation of a proof of concept and an R&D ground for the proposed CLIC drive beam phase feed-forward scheme will begin. It is required to reduce phase variations and the resulting luminosity loss [2, 3]. Naturally, the main challenge is the bandwidth of its components and of the whole system. It includes the amplifiers that need to deliver the highest possible power to ensure the feasibility of the system.

Due to building constraints the system installed at CTF3 utilizes the pre-existing four bend dog-leg chicane in the transfer line TL2, as opposed to a four bend C-chicane in the CLIC scheme [4]. Nevertheless, this design will deliver sufficient performance for the system tests and the results will be directly applicable to CLIC [4].

The CTF3 feed-forward scheme consists of three fast phase monitors [5, 6], a digital processor, two amplifiers and two electromagnetic strip-line kickers [6] placed in the chicane. The monitors and kickers are designed and fabricated by INFN/LNF Frascati, and the processor and amplifiers by the John Adams Institute and Oxford University. The phase monitors will be installed at three different locations. The first one will be placed in the transfer line between the Stretching Chicane and the Delay Loop (DL). It provides the measurement of the drive beam phase that is used by the digital processor to calculate the necessary correction. The second monitor is placed immediately prior to the correction location to verify that the phase error is not altered at this point. The last monitor measures the effect of the applied correction and will be installed at the beginning of the Test Beam Line. The two kickers will be placed prior to the first and last dipoles of the chicane. By altering the voltage (as calculated by the digital processor) applied to the two kickers the time of flight of the beam through the chicane can be varied. At a maximal voltage of ±1.2 kV the kickers will be able to deflect the drive beam by ±1 mrad. The feed-forward system will be first proven using uncombined beam to avoid any unnecessary issues connected to the recombination since the phase to be corrected is measured prior to the DL and Combiner Ring (CR). In the second stage the system will be implemented for the combined beam. The latency of the feed-forward system based on cable lengths and the latencies of the components is below 280 ns, which is well within the 380 ns beam time of flight between the pickup and the correction.

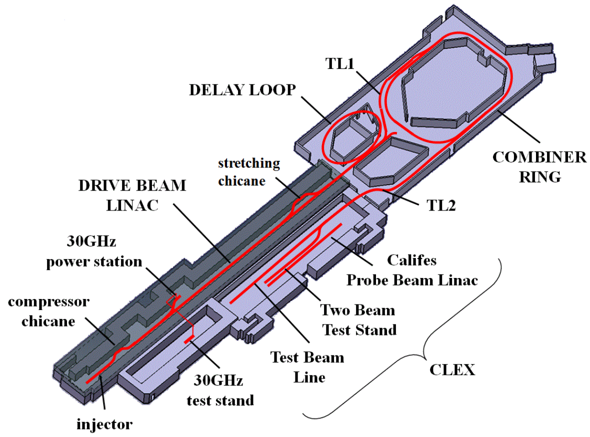

Figure 1: Layout of CTF3.

The kicker amplifiers for the feed-forward system are designed to provide high power at high bandwidth with a nominal peak power of 65 kW, to give to the kickers a dynamic range of at least ±1 mrad with the 125 MeV beam, and a large signal bandwidth of >50 MHz. The amplifiers will operate over the full 1.2 μs pulse duration for the uncombined beam at CTF3, but with full performance only specified over a 280–420 ns section of the pulse. The amplifier system will consist of four parallel modules, each with its own power converter and output transformer, which will connect to a common output power combiner/transformer. There will be a separate drive and

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control module, and an external 50 W DC supply. The output stage of the amplifier module will consist of two 1200 V SiC FETs driven by low voltage Si FETs, and a nominal peak power of 18 kW per module. Droop in the output transformers will be limited to <10 % over the full pulse duration. The target bandwidth will be at least 50 MHz, but will be less for large changes in signal amplitude due to slew rate limitations.

The kicker amplifiers will be driven by the digital processor. This is a custom digitiser and feed-forward controller based around a Xilinx Virtex-5 FPGA. It has nine analogue input channels, with digitization performed using ADCs with a maximum conversion rate of 400 MS/s and 14-bit resolution, and also four analogue output channels, using 14-bit DACs which can be clocked at up to 210 MHz. The FPGA logic operations can be clocked in the range 200–400 MHz, and for convenience a system clock will be chosen which has a period that is a sub-multiple of the sub-pulse length at CTF3, and that can be derived from the 3 GHz reference. The feed-forward algorithm will allow for operation on both uncombined and combined beam. For combined beam, measurements from corresponding sections of the different sub-pulses will be averaged together, mimicking the interleaving action of the DL and CR in CTF3.

LATTICE DESIGN

As there was not enough space to insert additional elements in the existing line its rearrangement is necessary. All quadrupoles currently connected in series will be independently powered. Large aperture quadrupoles and magnetic correctors are to be installed around the kickers. The former are needed to preserve the lattice functionality and the latter facilitate commissioning of the optics and a later implementation of a slow feed-back, in case the beam phase drifts outside of the feed-forward range. The key lattice parameter for the feed-forward system is the transfer matrix coefficient R_{52}, which relates the length of the trajectory through the chicane to the given kick. It should be as large as possible since it defines the range of the correction possible for the available kick strength. A target of $R_{52} = 1.2$ was used in the conceptual design so that the maximal ± 1 mrad kick results in a path length change of ± 1.2 mm, which corresponds to a phase correction range of $\pm 17.4^o$ at 12 GHz. The amplitude of the two kicks should also be equal, meaning that $|R_{22}| = 1$, and to ensure that the correction does not change the downstream orbit R_{21} must be zero. Additionally, due to the large energy spread of 1% r.m.s. at CTF3 the dispersion through the chicane should be kept as low as possible and below 2 m. To maintain optics matching there must also be no dispersion or its divergence at the exit of the chicane and ideally this should be the case independent of the kick amplitude.

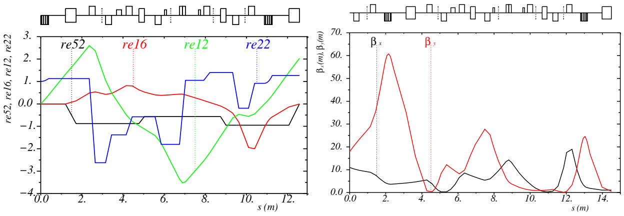


Figure 2: Example optics of phase feed-forward region.

In the conceptual phase an adequate optics was prepared. However, the technical constraints related to vacuum and alignment forced compromises in the original design. It was not possible to find optics satisfying all the above constraints. Namely, for $R_{52} = 1.2$ the dispersion reaches almost 3 m. In consequence the system will be operated with $R_{52} \approx 1.05$, which corresponds to a phase correction range of $\pm 15^o$ at 12 GHz. Figure 2 shows this example optics. It is important to stress that the range of the correction is not a crucial parameter for the proof and testing of the feed-forward concept [4]. A larger range would only facilitate the implementation of this system in routine CTF3 operations.

PHASE MONITORS PERFORMANCE

All three phase monitors were initially installed in series in between the Stretching Chicane and the Delay Loop, allowing necessary cross-checks. Each monitor has 4 output wave guides. Both horizontal and vertical pairs are connected to hybrids that output sum and difference signals. In this way the dipole mode, which is calculated to be -25dB relative to the monopole mode, is filtered out in the sum. It is mixed with a 12 GHz local oscillator locked to the master 3 GHz CTF3 clock, yielding signal proportional to the beam phase. At the same time the sum signal power is measured since the mixer output, and hence the phase calibration, depends on it. The power of the difference signal, which is proportional to the position offset, is also measured with a diode. All the above signals are sampled with 250 MHz ADCs.

The monitors were calibrated by injecting synthesized signals of different amplitudes with frequency close to that of the local oscillator. This allowed us to understand the influence of the signal power on the measured phase and cross-talk between the two signals, which needs to be corrected when reconstructing the phase. In order to verify the calibration, the obtained beam phase measurements have been compared with the ones reconstructed using resonant beam monitors. An agreement of 7% between the two has been found.

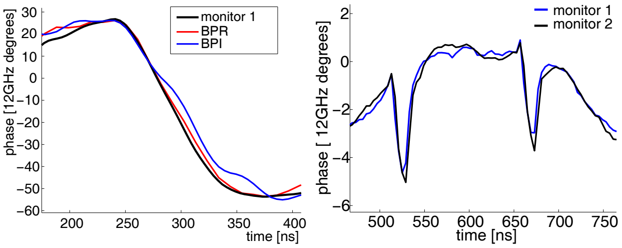
The resolution of the readout system due to the electronics was verified first and $\sim 0.3°$ at 12 GHz was found. It is smaller than expected because the ADC signal input is currently 8 times smaller than the sampler range. Naturally, in order to improve it an adequate amplifier will soon be installed to match the levels. The resolution of the monitors was obtained by comparing the measured phases along the beam pulse amoung the monitors. Residual histograms were created on a point by point basis. The resulting resolution is $0.35°$. Subtracting the electronics resolution in quadrature brings it to the assumed $0.2°$. One of the monitors exposed much worse performance than the other two. The signal is about ten times noisier and the phase signal is systematically different, oscillating around the ones given by the other pickups. The same monitor was reported to have issues in fabrication, namely with the output port installation. Clearly, it should be excluded for the time being and repaired during the following shutdown.

The phase measurement is relative to the local oscillator, and naturally its stability plays a key role in the measurement accuracy. Also, calibration needs to be closely watched since it changes with the beam parameters that modify the produced RF, namely beam current and the bunch form factor. For the component tests the monitors are not required to be very accurate; the linearity and the resolution are the key points. The system must flatten any phase variation and any error from the calibration will eventually be corrected with a system gain that leads to minimum phase variation. However, the accuracy of the system is of great importance for the CLIC phase synchronization and it will be carefully examined in the following stage.

One of the possible issues for these devices is the influence of the beam position on the measured phase. For example, this occurs for an imperfect hybrid, which is practically always the case. Two magnetic correctors installed just before the monitors were used to perform the position scans. The quadrupoles after the monitors were powered off to reconstruct the trajectory independently of the machine model, and the upstream optics was adapted to yield a good beam transport. The ballistic beam was measured with two BPMs after the phase monitors. It allowed the precise reconstruction of the position offset, which was varied more than ± 3 mm in both planes and no statistically relevant effect was measured. The residual power in the difference channel at its minimum was measured and compared to the power at different offsets. This allowed us to get a precise measurment of the rejection level of the hybrid. By symmetry, the rejection of the difference signal in the sum port is the same. The phase change per mm beam offset was calculated to be 0.16^o/mm.

The CTF3 beam pulse by design bears a phase variation with a parabolic shape. The linearity was checked by observing the measured shape whilst simultaneously changing the phase of the local oscillator. The shape was altered by less than $\pm 1^\circ$ in a range of $\pm 70^\circ$.

The monitor bandwidths were checked using a beam pulse with an energy step in the middle, which in combination with the non-zero R_{56} of the stretching chicane creates a phase change proportional to the energy change. The accelerating RF power in CTF3 uses a pulse compression system. Its amplitude is controlled via its input phase. For the purpose of this measurement the pulse compression system for the last accelerating structures was programmed to give as sharp RF power change as possible. Of course, it is limited by the bandwidth of the phase shifters, klystron and accelerating cavity. However, it can be verified with the help of a BPM located at a large dispersion location, which in turn has proven sufficiently large bandwidth. Figure 3a shows the response of three different devices. The phase slope corresponds to 3.5 MHz bandwidth. On the other hand, very fast phase changes connected to the phase switches in the sub-harmonic bunching system have been measured, Figure 3b. They indicate that the bandwidth is at least 10 MHz. Unfotunately these features can not be measured with any other device to independently verify the monitors reading.



(a) (b)

Figure 3: Monitor response on energy step (a) and phase switches (b).

The final check of the monitor bandwidth will only be possible after they are installed in their final positions downstream of the DL, where a 3 GHz pulse can be split into two, with odd bunches bypassing it and even bunches being delayed. The DL circumference can be varied with a wiggler by up to ±7 cm. If the pulse length is equal to the DL circumference a 1.5 GHz train with twice the length and a sharp phase change in the middle is obtained, perfectly suitable for bandwidth measurements.

CONCLUSIONS AND OUTLOOK

The phase feed-forward system in CTF3 will be installed during summer 2013. It will provide proof of the concept and a test bench for component development. Beam phase errors within $\pm 15^o$ at 12 GHz and 30 MHz bandwidth can be corrected. Fast phase monitors have been installed and commissioned in CTF3, with measurements showing that their performance meets the specifications.

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REFERENCES

[1] Ed. G. Geschonke *et al.*, CERN/PS 2002-008
[2] D. Schulte *et al.*, MOP024, Proceedings of LINAC10
[3] CLIC Collaboration, CERN-2012-007
[4] A. Gerbershagen *et al.*, WEPPP066, Proceedings of IPAC12
[5] F. Marcellini *et al.*, WEPEB035, Proceeding of IPAC10
[6] A. Ghigo *et al.*, TUPC007, Proceedings of IPAC11
[7] A. Anderson *et al.*, MOPAN066, Proceedings of PAC07
[8] A. Anderson *et al.*, EUROTeV-Report-2008-095-1