THE CLIC DRIVE BEAM PHASE MONITOR*

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Abstract

In the two beam acceleration scheme the Main Beam must be precisely synchronized with respect to the RF power produced by the Drive Beam. Timing errors would have an impact on the collider performances. The Drive Beam phase errors should be controlled, by means of a feed forward system, within 0.1° (23fs @ 12GHz) to avoid a luminosity reduction larger than 2%. A beam phase arrival monitor is an essential component of the system. Its design has been based on the following main requirements: resolution of the order of 20fs, very low coupling impedance due to the very high beam current and integrated filtering elements to reject RF noise and weak fields in the beam pipe that could otherwise affect the measurements.

INTRODUCTION

The Compact LInear Collider CLIC is based on the two beam accelerator scheme: the RF power produced in the deceleration of a high current electron Drive Beam, is sent to 12 GHz RF sections to accelerate the Main Beam [1]. The synchronization of the Drive Beam respect to the Main Beam is mandatory in order to keep constant the main linac energy. Errors in timing and intensity of the Drive Beam lead RF phase and amplitude errors in the accelerating sections with the consequence of effective gradient change. Final Main Beam energy errors, combined with limited beam delivery system acceptance, can cause loss of luminosity. The RF jitter tolerance is given by the limitation to less than 2% of the luminosity loss and by the negligibility of the luminosity spectrum widening at collision [2].

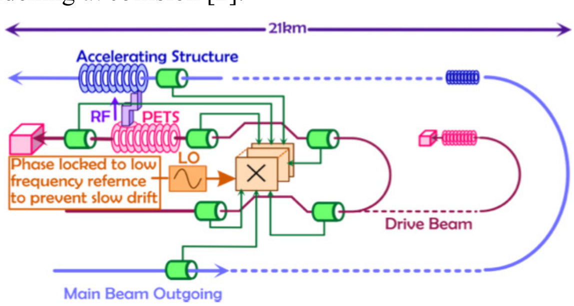

Figure 1: Overall CLIC layout and the placement of the detectors (green cylinders) in the turnarounds.

The CLIC single bunch RMS energy spread is of the order of $\sigma_E/E \approx 3.5\text{x}10^{-3}$. Due to the previous considerations the relative energy variation must be less than $\sigma_{jitt}/E < 4\text{x}10^{-3}$, corresponding to an effective gradient error of about $\Delta G/G \approx 4\text{x}10^{-3}$. This means that the coherent error of the RF phase all along the main linac has to not exceed about 0.1° corresponding to 23fs at the frequency of 12 GHz.

The synchronization between Drive Beam and Main Beam can be done with a feed-forward system that compares time measurements of both beams and then applies the proper phase correction to the Drive Beam. The front end of this system will consist of a monitor able to detect the bunch longitudinal positions.

The accelerator scheme and the places where the phase measurements could be taken are illustrated in Fig. 1.

The monitor should be characterized for the following main features:

- High resolution (of the order of 20 fs);
- Very low coupling impedance, to avoid problems coming from interaction with the high beam current;
- Rejection, by means of proper designed filters, of RF noise and weak fields that could originate spurious signals and affect the measurements.

THE PICK-UP DESIGN

The pick-up is the device that interacts with the fields induced by the beam and gives to the electronics a proper RF signal containing the information about the beam arrival time. It has been designed to reject the RF noise and wake fields in the working bandwidth and to have the lowest possible beam coupling impedance.

The beam induced signal is coupled out of the beam pipe through four slots equally distributed along the pipe circumference. The slot cut-off frequency is above 12GHz and the electromagnetic field at that frequency is evanescent in the slot. The field intensity at the slot end can be adjusted properly tuning the slot thickness (d).

A waveguide is then connected to each slot aperture, followed by a transition to a 50Ω coaxial line (SMA standard). A commercial vacuum feedthrough (MSSI part #853872) is placed in the coaxial section. The waveguide has been designed with double ridge geometry; this allows reducing its cross section and optimizing the transition frequency response.

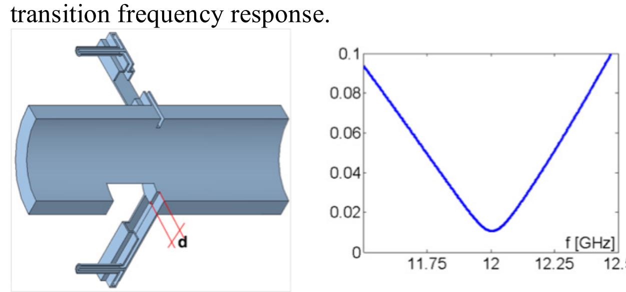

Figure 2: Geometry of the pick-up and reflection frequency response of the waveguide to coaxial transition.

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Cut views of the double ridged waveguide and of beam pipe with coupling slots are shown in Fig. 2 together with the transition frequency response (HFSS [3] simulation result). The reflection parameter results to be less than 0.02 in ±100 MHz bandwidth.

To keep the pick-up region free of the RF noise and beam generated wake fields, at least in the detection frequency range, notch filters are placed at both the pick-up sides.

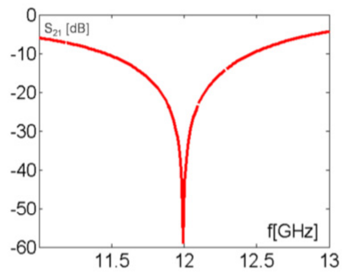

Figure 3: Transmission response of stop-band filter for the TM_{01} mode.

The notch filter is realized as a bump in the beam pipe. The dimensions of this bump are chosen to reject the 12 GHz frequency component of the noise. In general, one can consider that the different waveguide modes excited by the Drive Beam elsewhere are allowed to propagate along the beam pipe and thus the 12 GHz notch filter geometry needs to be tuned separately to reject any of them. As a solution the RF design of the several independent notches assembly is underway to allow the rejection of all the possible propagating modes. For illustration the TM01 mode notch filter transmission characteristic simulated with HFSS is shown in Fig. 3.

The most suitable place for installing and testing the monitor prototype is the CTF3 Drive Beam chicane region. However, the beam pipe radius of 20 mm in this region allows six modes propagation. Reducing the pipe radius down to 15 mm, only 3 modes (TE11, TM01 and TE21) can propagate at 12 GHz.

After the four pick-up signal combination, only the TM01 component will be naturally presented following the mode symmetry properties. This property can be used as a primary mean to reject the TE11 and TE21; however, the possible geometrical differences in 4 channels (the slot and waveguide misalignments and asymmetries, the cable lengths and the combiner errors) could lead to the non perfect cancellation of the four asymmetric signals for the TE modes and thus, the dedicated notch filters for each of these modes most probably will be needed.

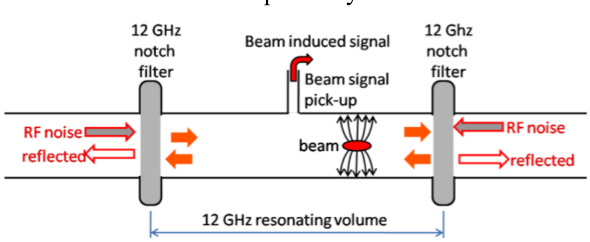

Figure 4: Working scheme of the pick-up with filters for noise rejection.

To establish the necessary 12 GHz resonant response of the system at the operating TM01 mode, we propose to place the notch filters at both sides of the pick-ups, thus providing a kind of closed volume, where the beam generated electromagnetic fields can build up resonantly in the frequency range of the filter rejecting band. The sketch of such an approach is shown in Fig. 4. Within this frequency range the resonating mode can be excited, if the distance between the two notches is equivalent to an integer number (n) of the given mode half wavelengths. The amplitude of the signal coupled out will depend on the particular distance between the notches. It can vary from zero, if an even number of half wavelengths is established in-between, to its maximum, if the half wavelength number is odd. The magnetic field plots in the case of TM01 mode is illustrated in Fig. 5.

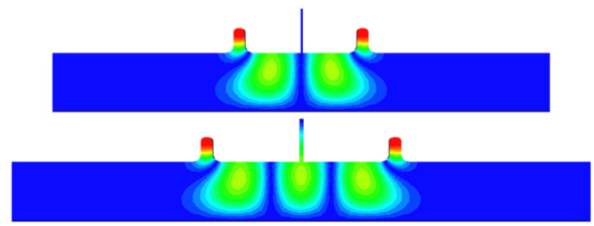

Figure 5: Resonating modes in the volume between the notches: n=2 (top) and n=3 (bottom).

This condition has been used to set up the amplitudes of the spurious (TE_{11} and the TE_{21}) mode resonant build up as close as possible to their minimum. On the other side, keeping the resonant conditions of the detecting TM_{01} close enough to its maximum, providing the Q – factor and the impedance of the detecting mode as high as possible, the typical values obtained from the simulations are Q=7000 and R=60kΩ for a structure build of aluminium. However, the needs for the Drive Beam time sampling resolution and the overall restriction for RF power extraction from the Drive Beam require, if possible, reducing both the Q-factor and the impedance values.

To do that, the few methods can be used:

- If being building of stainless steel, both the Q-factor and the impedance can be reduced by about a factor of 6;
- Coupling the resonating fields to the special external loads, or increasing the coupling to the pick-up waveguide network.
- Appropriate changing of the distance between the notches.

In the last case, the resonant frequency of the operating TM_{01n} mode can be shifted to a different frequency, where the filter has lower rejection, thus the fields are less sharply contained in the notch delimited volume. Following, the impedance maximum frequency is shifted and the amount of extracted beam power is rather reduced, but still could be enough to detect the proper signal. The pick-up impedance spectra for the cases with no coupling (solid lines), with coupling (β=5.6 at 12 GHz) to the waveguide (dashed) together with the filter rejection response (in solid red) are presented.

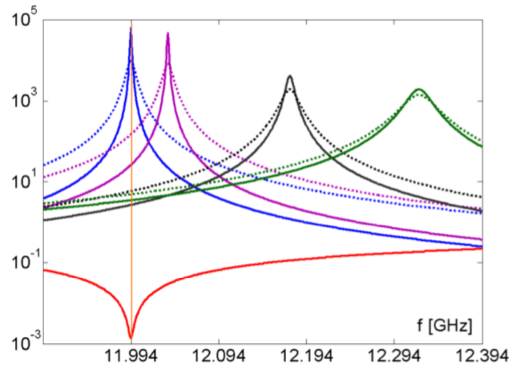

Figure 6: Different cases of monitor shunt impedance (vertical scale in Ohm) and notch frequency response.

DETECTION ELECTRONICS

In order to achieve the required very high resolution of this monitor, the design of the detection electronics is vital. Additionally, a very stable phase reference is required. Precision oscillators have been found which can manage less than 5 fs integrated timing jitter. A lot of progress has been made on femto-second stabilized reference lines in the last few years, in the context of XFEL construction. These links have been demonstrated over about a kilometer, but the possibility of extension over 24 km from the central distribution point cannot yet be inferred. However, for CLIC, the physical layout of the accelerator allows for an alternate phase reference, using low phase noise local oscillators, synchronized to the outgoing Main Beam rather than a central timing reference (see Fig. 1). The time between the passage of the outgoing Main Beam and the arrival of the Drive Beam (and the Main Beam again) is at most 160 μs. In Fig. 7 the effects of beam path filtering on the LO jitter are presented.

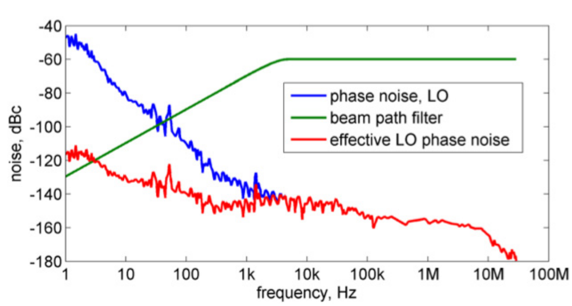

Figure 7: Oscillator timing jitter and beam path filtering.

For the signal detection itself, the performance is limited chiefly by device non-linearity and noise. While device non-linearity typically goes down with lower input power, the noise will increase relative to the signal. To mediate between these two conflicting goals, a strategy of parallelization will be used. The input signals from both the local oscillator and phase monitor will be split N ways, and detected on N mixers. The baseband signals will then be added together for an increase in signal to noise ratio. As we are mixing directly to baseband, the dominant non-linear term will be the second order term which mixes to DC, and which will thus be indistinguishable from the phase term. As this second order term is proportional to the square of the input amplitude, we must just pick an operating point where its contribution is small enough, and then parallelize over enough devices to bring down the noise. The characterization of the mixer linearity is shown in Fig. 8.

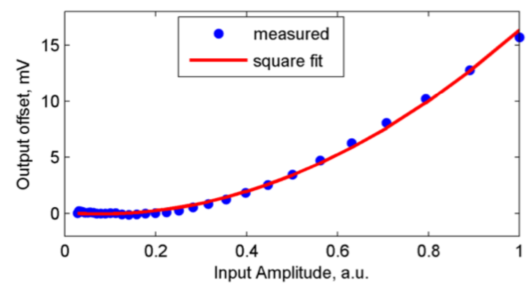

Figure 8: Mixer linearity measurements, second order term.

Detection electronics based on a similar approach, was already realized some years ago with 30 GHz RF and a wider detection bandwidth.

CONCLUSIONS

The monitor to be used in the feed-forward chain to control the synchronization between Main Beam and Drive Beam in CLIC has been conceived and designed to get, at the same time, the desired resolution, low coupling impedance and noise rejection.

Prototypes will be soon realized to check the simulation results and test fabrication techniques.

The electronics, already realized in case of 30GHz detection, has to be transferred at 12GHz.

The whole system will be tested in CTF3.

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