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Femto-second synchronisation with a waveguide interferometer

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ABSTRACT

CERN's compact linear collider CLIC requires crab cavities on opposing linacs to rotate bunches of particles into alignment at the interaction point (IP). These cavities are located approximately 25 metres either side of the IP. The luminosity target requires synchronisation of their RF phases to better than 5 fs r.m.s. This is to be achieved by powering both cavities from one high power RF source, splitting the power and delivering it along two waveguide paths that are controlled to be identical in length to within a micrometre. The waveguide will be operated as an interferometer. A high power phase shifter for adjusting path lengths has been successfully developed and operated in an interferometer. The synchronisation target has been achieved in a low power prototype system.

1. Introduction

Designs for CERN's compact linear collider CLIC [1] have electrons and positrons colliding with centre of mass energies between 280 GeV and 3 TeV. Interacting beams will have a crossing angle of θ_c = 0.02 radians. For the 3 TeV centre of mass design, bunches have vertical and horizontal beam sizes at the interaction point before the pinch of $\sigma_y = 1$ nm and $\sigma_x = 45$ nm respectively and a bunch length of $\sigma_z = 44$ μm. The slender profile of the bunches at the interaction point (IP) means that if they retain their crossing angle at the IP then luminosity will be reduced to just 10% of what could be obtained when the bunches are sheared into alignment with a z dependent transverse displacement. Crab cavities placed in the beam delivery lines before the IP deliver z dependent transverse momentum leading to bunch alignment at the IP [2]. Linear collider crab cavities are placed before the final focus quadrupoles and in a region of high β [3]. If the phase of a crab cavity is not exactly 90° from the phase of maximum possible deflection then the bunch receives a shear (or pseudo rotation) about a point that is not its geometrical centre resulting in an average deflection at the IP. If two bunches that should collide have differing average deflections then their axial centres miss each other at the IP. If the two crab cavities on opposing linacs are synchronised to each other but bunch arrival times vary independently by a small amount, then the bunches still collide head on but at a point that is transversely and longitudinally displaced; the transverse displacement from the IP becomes identical for the two bunches at the instant they collide [4]. Crab cavities are applicable to circular colliders as well as linear colliders [5–7]. It should be noted that for the LHC Hi-Luminosity upgrade which will use crabs cavities, synchronisation is not critical as bunches are much wider and the crossing angle is much smaller than those needed for CLIC. The operation of a Crab cavity in a circular machine has been demonstrated at KEKB [8].

Not including vertical offsets and bunch pseudo-rotation errors then (1) determines the maximum allowable r.m.s. cavity to cavity phasing error $\Delta\phi_{\rm rms}$ as a function luminosity reduction factor $S_{\rm rms}$, where f is the RF frequency. The target $S_{\rm rms}$ value for the crab cavities is 0.98. For 12 GHz RF (1) gives the maximum acceptable cavity to cavity phase error as 0.019 degrees which corresponds to 4.4 fs.

$$\Delta\varphi_{rms} = \frac{720\sigma_x f}{c\theta_c}\sqrt{\frac{1}{S_{rms}^4}-1} \quad \text{degrees.} \tag{1}$$

This paper proposes the operation of an interferometer inside the high power waveguide that distributes power to the crab cavities. This allows accurate synchronisation to be maintained. Key aspects of the interferometer are a means of measuring phase difference between reflected signals with an accuracy of 10 milli-degrees on a timescale less than that where the waveguide might move by such an amount and

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the development of a high power phase shifter. This paper demonstrates the interferometer concept with a prototype system. Section 2 discusses the powering of the crab cavities for CLIC. Section 3 discusses waveguide distribution options. Section 4 describes an implementation of a waveguide interferometer at CLIC. Section 5 describes the development of a high power phase shifter and its actuation. Section 6 describes how phase difference is measured and describes the experiment to test feasibility. Section 7 describes operation of the controller giving results for optimisation. Section 8 gives results from stabilisation tests.

2. CLIC RF layout

The CLIC crab cavities require multi-MW X-band RF pulses at 11.9942 GHz lasting at least 156 ns and repeated at 50 Hz. This could be provided either by klystrons or by a drive beam and PET structures [1]. The beam delivery system for CLIC will be several kilometres in length and hence the drive beam for the main linac is not easily made available near the IP. In addition, phase jitter generated in the PET structures is currently too large for the phase synchronisation target to be met [9]. Klystrons have phase jitter on their output coming from modulator ripple. Whilst in principle this can be corrected, the difficulty of making an accurate phase measurement and correcting phase on a timescale much less than 156 ns looks insurmountable. The proposed solution is to split power from a RF single source to drive crab cavities on each linac. The RF source might be a single 50 MW XL5 klystron [10] or power combined from multiple smaller klystrons [11]. This is similar to the proposal for synchronising the NLC crab cavities [12]. When one source drives both cavities and it takes the same time for the power to propagate from the klystron to each crab cavity then phase jitter arising from the klystron is identical for each. This means that positron and electron deflection arising from klystron jitter are identical and luminosity is maintained. If the RF length of the two paths from the klystron to crab cavities on the two linacs varies, then one phase moves with respect to the other, deflections of the beams differ and luminosity is lost. Importantly the RF path lengths from the klystron to the two cavities must be kept equal.

Fig. 1 shows the layout of the CLIC interaction region with 2 detector caverns. The klystron for the crab cavities is likely to be positioned at the back of one of the caverns in a bunker. The crab cavities are in the tunnel 23.4 m from the IP. The shortest distance from a possible location for the klystron to a crab cavity on the linac assuming 9 m of height change is 51 m.

As waveguides will be subject to vibration and temperature change then they will contribute to phase errors between the crab cavities. For this reason one wants to keep the waveguide length after the division taking power to individual cavities as short as practical. The most straightforward layout is to split the waveguide and hence the power on the side of a detector cavern closest to the beamline. The waveguide split needs to be central so that phase fluctuations arrive at the two cavities at the same instant. The split will need to be above the moveable wall which is at least 9 m above the beamline. Waveguide must be taken through bore holes to the crab cavities. The distance from the split to the cavity, following the waveguide, as shown in Fig. 1 will be approximately 35 m.

For a waveguide group velocity of 2.5×10^8 (Rectangular waveguide WR90 TE01) then the energy for the 156 ns RF pulse that will pass through the crab cavity occupies a length in the waveguide of 39 m. This means that the energy that will maintain the field in the cavity while the bunch train is passing has been completely determined before anything can be known about the cavity phase at the location of the klystron. The length of the waveguide also means that one does not need to worry about reflections from one crab cavity influencing the other crab cavity. The waveguide from the klystron to the splitter would be optimised for low loss whilst the waveguide from the splitter to the cavities must be optimised for phase stability.

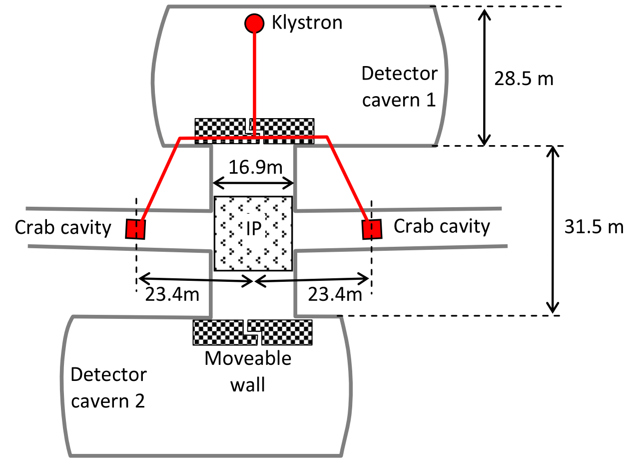

Fig. 1. (colour on line) Plan of CLIC interaction region with crab cavities marked.

3. RF system and waveguide distribution

Temperature, pressure and potentially ground motion and vibration affect the phase velocity of RF propagating in a waveguide by changing its physical dimensions. Dimensional stability depends on the choice of waveguide. The expansion coefficient of copper is 17 ppm/K. Power loss during transmission is also an important consideration when choosing the waveguide. Table 1 gives variation in phase transit times for 35 m of copper and copper coated INOVAR® waveguide following a temperature change 0.3 °C. This is a realistic limit on the degree of temperature control available in the tunnel.

Standard WR90 and other rectangular waveguides are least sensitive to temperature variations, carry the fewest modes, but have high transmission losses. Cylindrical waveguides have much lower losses when propagating the low loss TE01 mode, but have higher sensitivity to temperature variation. Multiple modes and hence potential mode conversion is an issue for the low loss transmission options. Unwanted modes travel at different phase velocities to the main mode. These modes then reach the cavity with a different phase and if they transfer energy into the cavity then a phase error is incurred.

Thermal expansion can be reduced by enclosing the waveguide in a thermal jacket containing a high heat capacity material or one at its liquidus temperature so that heat is absorbed with minimal temperature rise. Another solution is to use controlled expansion alloys such as INVAR (α = 1.2 ppm/K), INOVAR® (α = 0.65 ppm/K) and INOVCO® (α = 0.55 ppm/K) where α is the thermal expansion coefficient. These alloys have a high electrical resistivity $\sim 8 \times 10^{-7}$ Ωm so would need to be coated with copper or silver. Whilst the use of controlled expansion alloys will almost negate the effect of temperature variation, it will not negate movement from other causes such as tides and vibration.

4. CLIC crab cavity synchronisation scheme

In order to synchronise RF power to the CLIC crab cavities, continuous active control of the RF path length to each cavity from where power is split is expected to be necessary. The RF path length must be measured and adjusted at the micrometre level. A method to do this is by running an RF interferometer in the waveguide. We have been unable to identify literature on waveguide stabilisation with a microwave interferometer. There is however considerable literature on microwave interferometry and recent literature on measuring and cancelling phase noise from oscillators [13].

A frequency must be chosen for our interferometer that propagates as a single mode in the waveguide with no conversion to other modes and that is reflected by the crab cavities. A crab cavity prototype that