THE IMPACT OF LONGITUDINAL DRIVE BEAM JITTER ON THE CLIC LUMINOSITY

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Abstract

In the Compact Linear Collider (CLIC) now under study at CERN, the RF power which accelerates the main beam is provided by decelerating a high current drive beam. Errors in the timing and intensity of the drive beam can turn into RF phase and amplitude errors that are coherent along the whole main linac and the resulting error of the final beam energy, in combination with the limited bandwidth of the beam delivery system, can lead to a significant loss of luminosity. We discuss the stability tolerances that must be met by the drive beam to avoid this loss. We also examine one of the most important sources of this jitter, which stems from the combination of RF jitter in the drive beam accelerator and subsequent bunch compression. Finally we give details of a potential feedback system that can reduce the drive beam jitter.

MAIN LINAC RF JITTER TOLERANCE

The RF can jitter in phase and amplitude; both result in a change of the effective gradient. The RF jitter tolerance is given by two main constraints. First, the luminosity loss should be limited to less than 2%. Second, the energy jitter should not lead to a significant widening of the luminosity spectrum at collision. Since the mean RF phase in the linac is about $15°$, a coherent error of the RF phase all along the main linac of $0.225°$ corresponds to an effective gradient error of about $\Delta G/G \approx 10^{-3}$. The final energy error and the luminosity loss will be quite similar in the two cases.

In CLIC the single bunch RMS energy spread is about $\sigma_E/E \approx 3.5 \times 10^{-3}$. Consequently a beam energy jitter of $\sigma_{jitt}/E \approx 1 \times 10^{-3}$ leads to a negligible broadening of this spread, while $\sigma_{jitt}/E = 2 \times 10^{-3}$ results in probably acceptable but noticeable change of the total spread to $\sigma_E/E \approx 4 \times 10^{-3}$. We prefer to aim for $\sigma_{jitt}/E \leq 10^{-3}$.

To estimate the luminosity loss resulting from the RF jitter integrated simulations of the main linac, beam delivery system and beam-beam interaction have been performed, using PLACET [1] and GUINEA-PIG [2]. It has been found that the jitter tolerance arising from the luminosity loss due to multi-pulse emittance growth in the main linac is more relaxed than that from the above energy stability [3]. However, the limited bandwidth of the current beam delivery system results in a tighter energy error tolerance of $\sigma_{jitt}/E = 0.7 \times 10^{-3}$ for 2% luminosity reduction [5], see Fig. 1. This limitation is to a large extent due to the collimation system. Removing it from the simulation yields a tolerance of $\sigma_{jitt}/E = 1.2 \times 10^{-3}$.

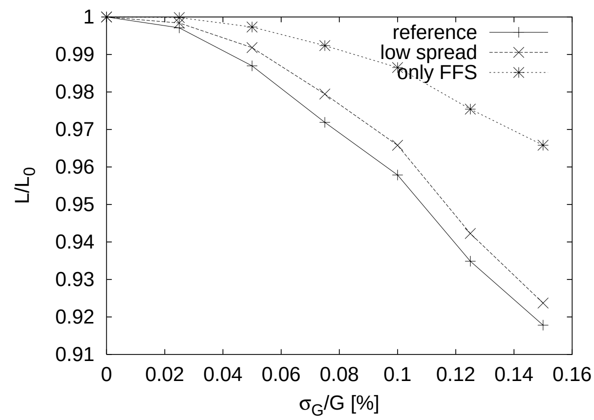

Figure 1: The relative luminosity as a function of a coherent gradient error in the main linac.

Table 1: Some important drive beam parameters.

parameter	symbol	unit	value
particles per bunch	N	[10^{10}]	6
energy before DBA	E_0	[MeV]	50
energy after BDA	E_f	[MeV]	2000
bunch length before DBA	$\sigma_{z,0}$	[mm]	4
bunch length after DBA	$\sigma_{z,f}$	[mm]	0.4

DRIVE BEAM TOLERANCES

The RF phase and amplitude in the main linac depends directly on the drive beam; the drive beam intensity and phase tolerances are hence $\delta I/I \leq 10^{-3}$ and $\delta\Phi \leq 0.225°$ (equivalent to $\delta z \leq 6\mu\text{m}$), respectively. After a short overview of the drive beam generation system one of the main jitter generation mechanisms will be discussed, focusing on coherent errors of the whole drive beam.

The drive beam is generated in a complex that is located centrally between the two linacs, for parameters see table 1. Each 92μs long drive beam pulse is produced in the drive beam injector complex and then accelerated in the drive beam accelerator (DBA), with an RF frequency of $30.0/32\text{GHz} = 937\text{MHz}$. In a delay loop the pulse is then split into 130ns long sub-pulses. At the end of the delay loop these pulses are pairwise merged forming new pulses of 130ns length but with twice the previous bunch frequency. In two following combiner rings 16 of these new pulses are again merged, increasing the beam intensity as well as the bunch frequency by another factor of 16. Each of the generated 22 pulses is then sent through a transport line to the start of one drive beam decelerator, where it will arrive in time to produce the RF power needed for the main beam.

Table 2: The parameters of the two drive beam bunch compression stages. The tolerances for a coherent error causing an energy error in the main linac of $\delta E_f/E_f = 0.001$ are also given. Full beam loading was assumed.

variable	unit	first	second
L_1	[m]	2	16
G_1	[MV/m]	13	13
ϕ_1	[°]	60	-60
$R_{56}^{(1)}$	[m/MV]	0.0022	-0.00025
$\delta N/N$	$[10^{-3}]$	0.3	
δz	[μm]	70	
$\delta E_0/E_0$	$[10^{-3}]$	6	
$\delta G/G$	$[10^{-4}]$	200	2.8
$\delta\phi$	[°]	0.8	0.01

Short bunches of $\sigma_z \approx 0.4\mathrm{mm}$ are required in the decelerators for efficiency, while the drive beam bunches are likely to be as long as $\sigma_{z,0} \approx 4\mathrm{mm}$ [6] at injection into the DBA. The required bunch compression can turn energy errors into longitudinal bunch position and hence RF phase errors. If all the compression were performed after the DBA without further RF one would require a total compression $R_{56} = 0.4\mathrm{m}$ for the maximum allowed correlated beam energy spread of $\sigma_E/E = 0.01$. The drive beam mean energy error tolerance would then be $\delta E/E \approx 1.6 \times 10^{-5}$, putting strong limits on the DBA RF phase and gradient tolerance; also the beam current needs to be stable to this level, since the DBA is fully loaded.

To develop a first order concept of the bunch compression system a simple program has been developed to simulate longitudinal drive beam effects. It takes the single and multi-bunch beam loading into account and assumes compression chicanes and bends which couple only the longitudinal particle positions and energies linearly with a given R_{56}. With the bunch compressor detailed in table 2, a number of tolerances can be largely relaxed. The compressor uses opposite RF phases in the two stages, and is optimised to be independent of the initial energy error of the bunches. The charge stability tolerance is somewhat tighter than that required from the amplitude stability (10^{-3}). It can be relaxed if structures with less than 100% beam loading are used; reducing the loading to 75% (in power) would increase the tolerance to $\delta N/N = 6 \times 10^{-4}$ and require only $\approx 30\%$ more compressor power.

The remaining tight tolerance is the RF phase stability; this is unavoidable because the RF phase defines the final timing of the bunches. It could only be avoided if no bunch compression were required, e.g. by using an RF injector that could produce bunches with $\sigma_z \leq 0.4\mathrm{mm}$. However, it is not obvious that such an injector can be constructed. Also the longitudinal jitter tolerance for the bunches of this injector would be very tight, namely $\delta z \leq 6\mu\mathrm{m}$.

The tolerance of the main beam to a longitudinal shift of the whole drive beam pulse can be largely improved by using the drive beam to generate the power for the main beam bunch compressors. If the bunch compressor beam loading effects are small, the main beam bunches will always be set to the same drive beam phase. If one drive beam generator is used for both main linacs, even the relative timing between the electron and positron beam will be correct.

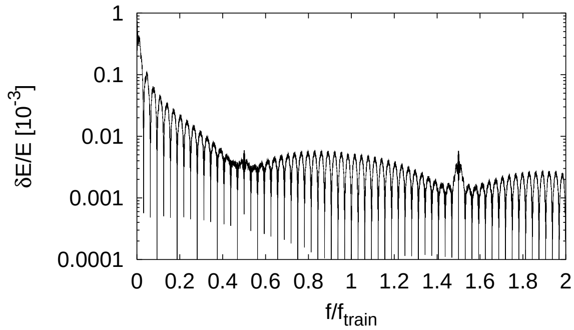

Figure 2: The maximum main beam final energy error due to the drive beam phase jitter resulting from an RF phase error of $0.01°$ in the second drive beam bunch compressor stage as a function of the frequency of the RF error. The results for an RF amplitude error in the same stage of 2.8×10^{-4} are comparable.

If an error is not coherent along the whole drive beam pulse, the effect on the main beam is more complicated since the effect of the merging of drive beam sub-pulses needs to be included. In this case, the effect of most frequencies averages out, except for those close to harmonics of the sub-pulse frequency $f_{train} = 1.0/130\mathrm{ns}$. The main linac energy variation is shown in Fig. 2 for the important example of a $0.01°$ klystron RF phase jitter of the second bunch compressor stage. The bunch compressor structures were modelled as constant impedance structures with no losses. A fill time of twice the sub-pulse length ($260\mathrm{ns}$) was used. This efficiently suppresses the dangerous harmonics of the sub-pulse frequency. As can be seen, the effect is strongly reduced for high frequencies. But the tightest low frequency tolerance is $0.013°$ and is barely visible in the figure. However, these low frequency errors can be controlled using a feedback on the klystron level [7].

PHASE COMPENSATION FEEDBACK

Another improvement of the tolerances can be expected from beam-based feedback. First, the phase of the RF needs to be measured. This can be achieved by fully compressing the beam and measuring its phase. The bunches will then need to be uncompressed again and recompressed before the decelerator. This would be a convenient choice if the beam is fully compressed in the DBA. Another option would be to measure the phase and the beam energy error in a dispersive point, so that one can predict the phase after compression. One can also measure the phase at two points which are separated by some R_{56}. Several possibilities exist to correct the measured phase error, e.g. one can modulate the beam energy by use of an accelerating struc-

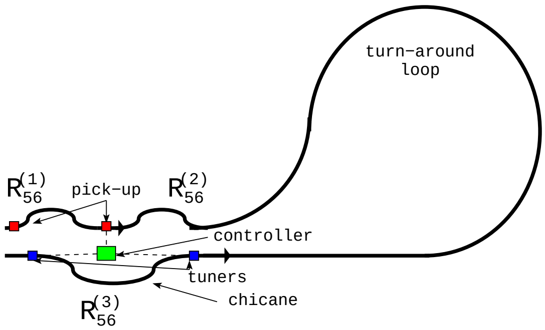

Figure 3: An example layout of a phase feedback.

ture before the final bunch compression. Or one can use transverse deflectors to introduce a half-sine-wave perturbation in the central orbit in a dispersive and anisochronous section of beam line. To first order the path length between the deflectors will be proportional to the amplitude of the deflection. The amplified measured phase signal must arrive at the deflectors before the beam. Such a feedback can be placed in many locations, e.g. before or after the combiner rings or at each turn-around that bends a drive beam pulse into a decelerator; the optimum will have to be determined. Here we present the example of the feedback in the final turn around, with the detector before and the deflectors in a chicane of four bending magnets as shown in Figure 3.

This chicane would contain bends to convert transverse deflection to path length. It would have to be achromatic and isochronous in its overall properties to avoid compression or further phase errors. However, it would contain a non isochronous section between the deflectors that need to be spaced in betatron phase by exactly π. It would be convenient if the total bending angle would be zero to preserve the line of the turned around beam.

To introduce significant path length, the bending angles, θ, in the chicane must be large since they contribute a term proportional to $\theta \sin \theta$ to the ratio between path length and deflection. The focusing lattice into which the magnets are embedded is not trivial and must be chosen to have two points exactly π apart for the deflectors.

A much simpler alternative is to place the deflectors in the final quadrant of the turn-around lattice thus saving the need for an additional chicane. In order to demonstrate the feasibility we chose the final quadrant of the combiner ring lattice, which is achromatic and isochronous from end to end. It is rather easy to find two places for the deflectors which are exactly π apart, (D1 and D2) in Fig. 3.

For the matrix element that relates horizontal deflection to path length, we find $R_{52} = \Delta s/\Delta x' = -0.756\mathrm{m}$, using MAD8 to compute this value from D1 to D2. This would provide a range of path length adjustment of $\pm 100\mu\mathrm{m}$ with deflectors of $\pm 0.13\mathrm{mrad}$.

The transverse deflectors we consider are based upon an S-band structure designed for use as part of an RF separator

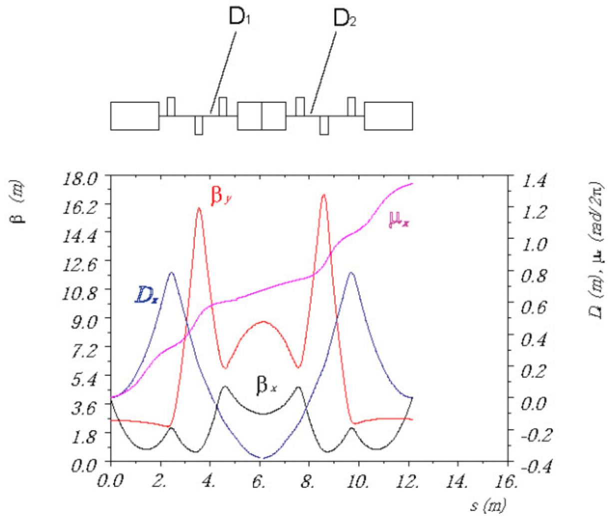

Figure 4: The lattice of the feedback.

project [8]. The use of wall mounted stripline deflectors or fast pulsed magnets could be feasible, such as those used in the TESLA damping ring. A $15\mathrm{GHz}$ scaled down version of the S-band deflecting cavities has been calculated[9]. It has an aperture of $9.4\mathrm{mm}$ and a length of $0.65\mathrm{m}$; with an input power of $1.82\mathrm{kW}$ it could deflect the $2\mathrm{GeV}$ beam by $0.13\mathrm{mrad}$.

CONCLUSION

The longitudinal jitter of the CLIC drive beam has to be strictly limited in order to avoid significant luminosity loss. One of the main sources for such jitter is the combined effect of energy errors during drive beam acceleration and the bunch compressor. Some examples of means to cope with the problem have been shown.

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