ALIGNMENT AND WAKE FIELD ISSUES IN THE CLIC RTML

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Abstract

At main linac injection the particle beams need to stay within tight tolerances for the transverse emittances and the pointing stability. We study how these tolerances influence alignment requirements for the RTML components and the stability of the beams entering the RTML. An emphasize is put on the booster linac and the RF cavities of the second bunch compression stage since short and long range wake fields might strongly influence beam dynamics in these parts of the RTML.

INTRODUCTION

After creating the lattices for the CLIC RTML and optimizing them regarding to their undisturbed performance only a few imperfections had been studied [1]. Since then mainly beam position jitter, static and dynamic alignment of several sub-systems have been simulated putting an emphasize on the impact of wake fields in misaligned RF cavities. These are the 2 GHz cavities of the booster linac, which accelerates the particles from 2.86 to 9 GeV, and the 12 GHz cavities of the second bunch compression stage (BC2), which are needed to induce an energy chirp.

Tight constraints are imposed on the performance of the RTML, particularly on the allowed emittance growth. Table 1 shows beam parameters as delivered by the damping rings, i.e. at the start of the RTML. Table 2 shows beam parameters as required by the main linac, i.e. at the end of the RTML. A sketch of the while RTML is shown in Fig. 1.
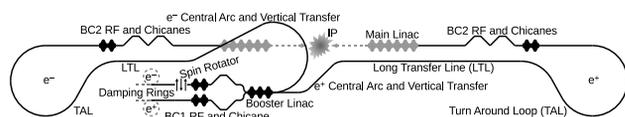

Figure 1: Conceptual layout of the RTML showing its main components.

MISALIGNMENT AND BEAM JITTER STUDIES

Studies of static and dynamic misalignment were performed for the booster linac and the BC2 RF due to the cavity misalignment leading to wake fields and for the turn around loops due to their complex lattices with strong quadrupoles and sextupoles. Since a jittering beam position

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Table 1: Beam Parameters at the Start of RTML

Property	Symbol	Value	Unit
Particle energy	E_0	2.86	GeV
Bunch charge	q_0	0.65	nC
Bunch length	σ_{s}	1800	μm
Total energy spread	$\sigma_{\mathrm{E,tot}}$	0.12	%
Normalized emittance	$\varepsilon_{\mathrm{n,x}}$	500	nm rad
	$\varepsilon_{\mathrm{n,y}}$	5	nm rad

Table 2: Required Beam Parameters at the End of RTML

Property	Symbol	Value	Unit
Particle energy	E_0	9	GeV
Bunch charge	q_0	> 0.6	nC
Bunch length	σ_{s}	44	μm
Total energy spread	$\sigma_{\mathrm{E,tot}}$	< 1.7	%
Normalized emittance	$\varepsilon_{\mathrm{n,x}}$	< 600	nm rad
	$\varepsilon_{\mathrm{n,y}}$	< 10	nm rad

also leads to wake fields the impact of this imperfection has been studied too.

Turn Around Loops

The particle energy in the turn around loops (TAL) is 9 GeV. Hence, it is in a regime where incoherent synchrotron radiation (ISR) is not negligible anymore and the design of the TAL lattices must be strongly tuned to reduce emittance growth due to ISR. That means, beam sizes in the dipoles have to be made small by utilizing strong focusing quadrupoles. On the other hand, to correct chromatic aberration by the quadrupoles strong sextupoles need to be integrated into the lattice. The current TAL lattice consists of 250 dipoles, 372 quadrupoles and 200 sextupoles distributed over a length of about 2 km. A sketch of a single arc cell of the TAL is shown in Fig. 2.

To estimate the level of static misalignment that can be allowed the magnets of the TAL have been randomly misaligned with a sigma of 100 μm for the dipoles and quadrupoles and a sigma of 50 μm for the sextupoles. Afterwards dispersion free steering (DFS) has been used for correction of the quadrupole positions. A BPM resolution of 100 nm and a BPM misalignment with respect to the quadrupole axis of 1 μm have been assumed. The remaining growth of the vertical emittance is around $\Delta\epsilon_{p90} = 1.2$ nm rad. A value that is on the edge of what can be allowed for a single source of imperfection in the RTML.

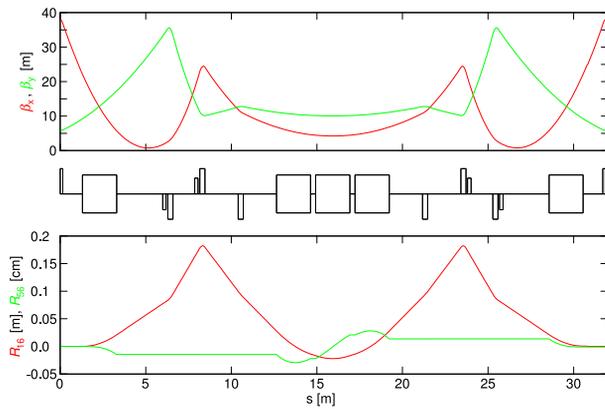Figure 2: Beta functions (top), dispersion and momentum compaction (bottom) along an arc cell.

Table 3: HOM Parameters in First and Last Cell of an Undamped Cavity

	f [MHz]	K [v/(pC m²)]	Q
First cell	2877	214.5	15966
	3653	38.7	24061
	4638	33.0	18773
	5036	0.0061	28178
	5051	0.0047	24914
Last cell	2991	276.5	18578
	3818	17.2	21149
	4801	91.4	15880
	5047	0.0085	28839
	5062	0.0101	24906

That means, the performance of the TAL lattice might not be sufficient. To improve the sextupoles have to get weaker, i.e. all the lattice has to be relaxed.

Since DFS requires special machine setup it can only be applied seldomly. During standard running of CLIC the only possibility is to use 1-to-1 steering or algorithms based on singular value decomposition (SVD). The level of dynamic misalignment that can be allowed has been estimated by misaligning all magnets randomly by $1~\mu$m and applying SVD. The growth of the vertical emittance is $\Delta\epsilon_{p90} = 0.6$ nm rad. Since the shot-to-shot alignment jitter will be a lot smaller than $1~\mu$m the emittance jitter should be acceptable. In any case, the assumption of random alignment errors is a worst case and a more realistic ground motion that includes correlations reduces emittance dilutions and beam position jitter strongly.

Note, that assuming a BPM resolution of 100 nm might sound exaggerated. But it has been specified that the position of the beams entering the main linac has to jitter by less than 10% of the rms beam size. Since in the vertical plane the beams are of micron sizes, at least some of the BPMs in front of the main linac must have a resolution in the range of 100 nm.

Booster Linac

The booster linac is required to achieve the main linac injection energy of 9 GeV. The same linac is shared by electrons and positrons. This is made possible by shifting the two incoming bunch trains in time. The booster linac consists of 276 2 GHz cavities running at an average gradient of 14.9 MV/m. They are embedded into a FODO lattice using 8 cavities per cell. The average beta function is about 16 m. The total length of the booster linac is about 538 m.

First studies on the impact of short range wake fields showed that dispersion free steering can reduce effectively vertical emittance growth to 1 nm rad (90th percentile). An RMS misalignment of the cavities and quadrupoles by $100~\mu$m and $100~\mu$rad was assumed. The BPMs need a resolution of $1~\mu$m. Including the effect of long range wake

fields doubled the vertical emittance growth in simulations, which is already too high but not too bad. The frequencies, amplitudes and Q-factors of the first five higher order modes have been derived from RF simulations for the first cell, the middle cell and the last cell. Values for first and last cell are summarized in Table 3. HOMs in the other cells were derived from interpolations.

While the simulation results looked promising, a calculation of the impact of long range wake fields based on the equations derived in Ref. [2] proved otherwise. The resulting amplification factors were $F_c = 3.8$ for a coherent shift of all bunches within a train, $F_{rms} = 1.7$ for the average amplification and $F_{worst} = 62$ for the worst combination of bunch misalignments along a train. To safely avoid amplification of incoming beam jitter the higher order modes in the cavities will need to be damped to Q factors below 30. The amplifications factors are reduced to $F_c = 1.0$, $F_{rms} = 1.1$ and $F_{worst} = 5.0$, which is with the specifications of $F_c < 1.5$, $F_{rms} < 1.5$ and $F_{worst} < 5.0$. HOM damping will be even more important for CLIC500 since the bunch charge will double. Other approaches like shifting HOM frequencies or increasing the frequency spread along a cavity were not sufficient. Also stronger focusing was not effective enough.

Bunch Compressor 2

The second bunch compression stage (BC2) compresses the bunches to the final length of $44~\mu$m. Its RF section is made of 78 12 GHz cavities which are 0.23 m long and run 90 deg off-crest at an average gradient of 94 MV/m. These cavities are of the same type as the main linac cavities for CLIC500. The high gradient is possible since in average no energy is extracted by the beam. Its value is sufficient to compensate for the impact of short range wake fields, which tend to lower the induced energy chirp.

The RF section of BC2 has never been well optimized which became apparent when we performed start to end simulations with incoming beam jitter. While this jitter was well transported through all other parts of the RTML, in the BC2 RF a considerable emittance dilution has been

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induced. Following these findings it was decided to use the same lattice as at the start of the nominal main linac, since this part of CLIC has already been extensively studied and optimized [3]. Due to the lack of HOM parameters long range wake fields could not be simulated.

Beam Jitter Simulations

After improving the RTML lattices we performed new simulations from RTML entrance to its exit. We used only the lattice for the electrons since it is more complex than the one for the positrons. These simulations include only short range wake fields to emphasize their possible impact. CSR and especially ISR are stronger sources of emittances growth. The incoming beam was jittering by 10% rms of its normalized beam size. Fig. 3 shows the development of the horizontal emittance along the RTML. The values are the 90th percentile of 400 simulations. For comparison the simulations were also performed without wake fields. Fig. 4 shows the same for the vertical emittance. As one can see the impact of short range wake fields is negligible. That the case with wake fields results in slightly smaller emittances is due to the fact that some of the lattice matching was done including short range wake fields. Hence, a small mismatch results if they are switched off. The spikes are artefacts in dispersive sections. It is the lattice itself that induces considerable emittance growth. That means, it is not perfectly matched and tuned.
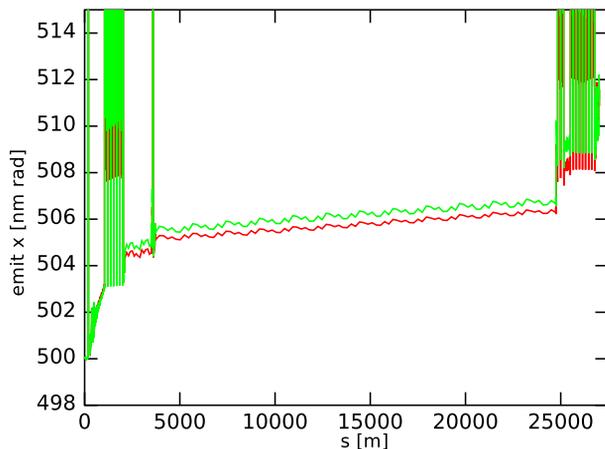

Figure 3: Development of the horizontal emittance of a single bunch along the RTML, with wakes (red) and without wakes (green).

From the phase space distributions obtained for different random offsets projected multi-bunch emittances can be calculated. For the calculation all phase space distributions of the individual bunches of a bunch train are projected onto each other including possible offsets. The resulting multi-bunch phase space distribution is used for emittance calculation. The assumed 10% rms position jitter leads at the RTML entrance to projected emittances which are 1% larger than the nominal bunch emittances. At the RTML exit without wakes fields we get an additional growth of
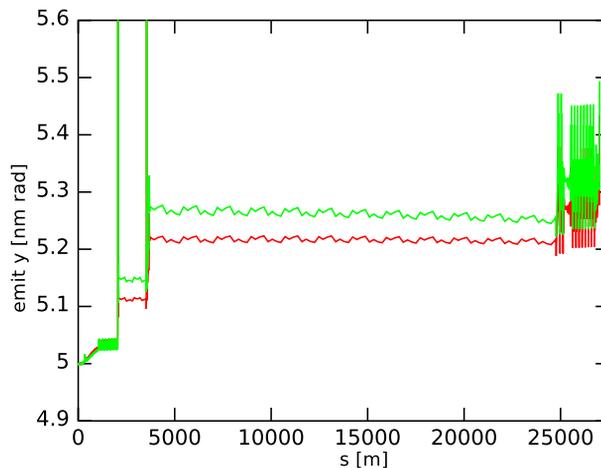

Figure 4: Development of the vertical emittance of a single bunch along the RTML, with wakes (red) and without wakes (green).

$\Delta\epsilon_{\text{proj,x}} = 3.6$ nm rad and $\Delta\epsilon_{\text{proj,y}} = 0.4$ nm rad. With single bunch wakes fields we get $\Delta\epsilon_{\text{proj,x}} = 3.8$ nm rad and $\Delta\epsilon_{\text{proj,y}} = 0.3$ nm rad. While the value for the horizontal plane might be acceptable, the one for the vertical plane is not and further lattice improvements need to be done. A major contribution is due to the arcs of the vertical transfer, which should not be too complicated to mitigate.

SUMMARY

After completion of the RTML lattices and first optimizations, more detailed studies of the impact of misalignment and incoming beam jitter have been performed. A couple of shortcomings were identified which stemmed mostly from wake fields. Accordingly, booster linac and BC2 RF have been revised. The BC1 RF has been adapted to the new booster linac lattice for consistency. The turn around loops remain to be improved. This has been tried but no satisfactory results have been obtained yet.

Simulations of incoming beam jitter reveal that after the reduction of the impact of wake fields now lattice tuning, matching and chromatic aberrations are not satisfactory.

In any case, the performance of the undisturbed lattices as well as their performance including imperfections is considered sufficient for the conceptual design report. Any larger changes to the RTML are postponed to after the CDR completion because some changes might have to be incorporated requiring revisions of several RTML lattices.

REFERENCES

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[3] D. Schulte, "Beam-Based Alignment in the New CLIC Main Linac", in proceedings of PAC09, May 2009