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CONCEPTUAL DESIGN OF THE CLIC DAMPING RING RF SYSTEM

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Abstract

In order to achieve high luminosity in CLIC, ultra-low emittance bunches have to be generated in both electron and positron damping rings. To achieve this goal, big energy loss per turn in the wigglers has to be compensated by the RF system. This results in very strong beam loading transients affecting the longitudinal bunch position and bunch length. In this paper, the conceptual design of the RF system for the CLIC damping ring (DR) is presented. Baseline for the CLIC conceptual design report (CDR) is discussed and the corresponding requirements for the cavities and the RF power sources are presented in order to meet stringent tolerances on the bunch-to-bunch phase and bunch length variations.

INTRODUCTION

Table 1: CLIC DR baseline parameters

RF frequency: f [GHz]	1
Circumference: C [m]	427.5
Energy : E [GeV]	2.86
Momentum compaction: α_p	1.28 x 10^{-4}
Bunch population: N_e	4.1 x 10^{9}
Number of bunches: N_B	312
Number of trains: N_T	2
Energy loss per turn: eV_A [MeV]	3.98
Energy spread in the bunch: σ_E/E [%]	0.12
Bunch length: σ_Z [mm]	1.8
RF voltage: V_C [MV]	5.1
Harmonic number: h	1426
Synchronous phase : φ [^{o}]	38.7
Synchrotron frequency: f_s [kHz]	3.45
Energy acceptance: $\Delta E/E$ [%]	2.34
Bucket length $2\Delta Z$ [mm]	70

In Table 1, parameters of the CLIC DR are presented [1]. The bunch spacing in the CLIC main linac is 0.5 ns which correspond to the bunch repetition frequency of 2 GHz. The parameters set presented in Table 1 correspond to a 1 GHz RF system where the bunch spacing is 1 ns. In this case, 2 trains of 156 bunches circulating in the DR symmetrically must be interleaved after extraction in order to provide nominal bunch train structure. A possible alternative to this baseline is based on a 2 GHz RF system. It has only one train of 312 bunches with nominal spacing. No train interleaving is required after the DR in this case. The main disadvantage of this alternative is that the peak current is twice higher than in the baseline case. This has strong implications for several subsystems, one of which is the DR RF system. In this paper, the baseline at 1 GHz with two bunch trains circulating in the DR is described. Several alternative solutions both at 1 and at 2 GHz are described elsewhere [2].

In addition, tight specifications from the Ring-To-Main-Linac (RTML) line and the main linac are set in order to provide nominal bunch parameters and bunch train structure in the main linac. Two specifications are of paramount importance for the DR RF system: 0.1° at 1 GHz (280 fs) RMS spread in the bunch spacing from the nominal value of 0.5 ns, and 2% RMS bunch length spread along the bunch train [3].

BEAM LOADING EFFECT

Voltage Modulation

Both high peak current and very high energy loss per turn contribute to a very strong loading of the cavity when the beam passing through. Strong voltage modulations are possible due to strong variation of the stored energy. The stored energy variation is expressed in terms of the beam parameters [2]:

$$\delta U = -\left(P_B - \langle P_B\rangle\right)\frac{N_B T_R}{N_T h} = -\frac{N_B N_e e V_A}{N_T}\left(1-\frac{N_B}{h}\right) \quad (1)$$

Then a condition to keep the RF voltage variations small in an RF system with constant input RF power is derived:

$$|\delta U| << U = \frac{V_C^2}{2\omega R/Q}\,. \quad (2)$$

In the following, R/Q of the RF system is optimized since all the other parameters in Eqs. (1) and (2) are specified in Table 1 and cannot be changed.

Bunch Phase Modulation

Variation of the RF voltage results in the variation of the bunch phase along the train. There are two contributions: First, the phase of RF voltage is directly affected by the voltage excited in the cavity by the beam. Second, since the energy loss per turn must be constant for all bunches along the train, the synchronous phase slips to compensate the RF voltage reduction due to beam loading. The sum of the two contributions gives the total modulation of the bunch phase [2]:

$$\begin{aligned}\delta\phi_B &= \delta\phi_1 + \delta\phi_2 \\ &= \frac{\delta V_C}{V_C}\left(\tan\phi + \frac{1}{\tan\phi}\right) = \frac{\delta V_C}{V_C}\frac{1}{\cos\phi\sin\phi}\end{aligned} \quad (3)$$

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Bunch Length Modulation

Modulations of the RF voltage also results in the RF bucket distortions which are schematically shown in Fig. 1. Since the energy spread in the bunch is constant related to radiation damping, the bunch gets longer if the RF voltage is reduced.

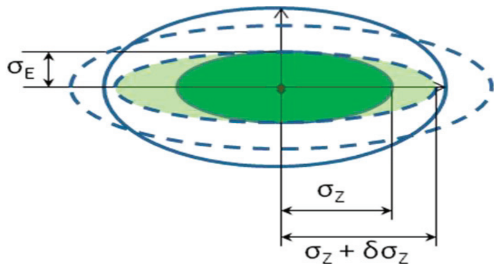

Figure 1: Distortion of the RF bucket and the bunch longitudinal phase space due to RF voltage modulation are schematically shown.

The effect of the bunch lengthening can be estimated analytically in the case of the small amplitude harmonic oscillations [2]:

$$\frac{\delta\sigma_Z}{\sigma_Z} = -\frac{1}{2}\frac{\delta V_C}{V_C}\frac{1}{\sin^2\phi} \tag{4}$$

DR RF SYSTEM PARAMETERS

The baseline solution proposed for the CLIC CDR is based on two bunch trains circulating the DR in the same direction with a delay equal to the half of the DR circumference. Since the bunch spacing in the trains is twice the nominal one, the peak current and so the peak beam loading power is reduced by factor 2. In addition, the RF system can be designed at the lower frequency of 1 GHz, which brings the advantage of providing more stored energy to cope with the strong beam loading effects. Thus, in the baseline, the DR RF system is designed in a way that the stored energy is so high that the RF voltage variation is kept small to minimize the transient effect on the beam phase to be below the specifications. The RF system is in principle close to the standard RF system for high beam current storage rings e.g. KEK-B low energy ring (LER) [4]. It is also proposed to use the same type of cavities: ARES-type, which provides low R/Q necessary to mitigate the strong beam loading effects [5]. Below the choice of basic parameters is shown in a few steps:

- The specification for the bunch phase variation is given as 0.1° RMS spread at 1 GHz. Since in the proposed RF system RF voltage modulations are small and very close to a linear variation from the first bunch in the train to the last one, the phase variation is linear as well. Knowing the distribution we can formulate the specification in a form corresponding to peak-to-peak variation of 0.3°, which corresponds to 0.1° RMS.
- Using Eq. (3) relative peak-to-peak RF voltage variation is estimated to be 0.26%.
- Using variation of Eq. (2) relative peak-to-peak variation of the total stored energy is estimated to be 0.52%.
- Eq. (1) is used to calculate the absolute peak-to-peak variation of the total stored energy to be 0.318 J.
- Knowing the relative and the absolute variation, the total stored energy itself can be calculated: 61.2 J.
- Finally, given the total stored energy and RF voltage, the total *R/Q* of the RF system is calculated using Eq. (2).

In order to derive the individual cavity parameters from the parameters of the total RF system, an estimate of the admissible RF voltage per cavity V_0 is needed. To get it, the ARES-type cavity originally designed for KEK-B RF system at 0.509 GHz [5] is scaled to 1 GHz and modified to reduce *R/Q*. In Fig. 1 of the Ref. [5], the original cavity geometry and some parameters are shown. The ARES cavity consists of three cavities: a storage cavity which operates at TE015 mode, an accelerating cavity operating at fundamental TM010 mode and the coupling cavity connecting the storage and accelerating cavities. It is equipped with HOM damping and tuning features. Furthermore, in Fig. 2, the process of cavity scaling and modification is schematically shown. It is done in two steps. First, all dimensions of the cavity are reduced as the ratio of frequencies. Making this scaling we assume that the admissible electro-magnetic field strength remains constant, so the RF voltage per cavity must be reduce linear with the frequency: $V_0 \sim 1/f$.

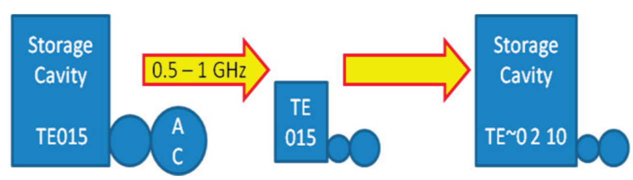

Figure 2: Two step processes of cavity scaling and modification for *R/Q* reduction is schematically shown.

Table 2: Parameters of the ARES cavity: I. Original parameters at 0.509 GHz, II. Parameters of the cavity scaled to 1 GHz, III. Parameters of the cavity modified at 1 GHz

	I	II	III
Frequency: f [GHz]	0.509	1	1
R_g/Q (circuit) [Ω] ($\sim f^0$)	7.4	7.4	0.925
Unloaded Q: ($\sim f^{1/2}$)	110000	78000	156000
Aperture radius: r [mm]	80	40	40
Gap voltage: V_g [kV] Nominal ÷ Maximum	500÷ 866	250÷ 433	250÷ 433

The corresponding scaling of cavity parameters is presented in Table 2, where the original parameters at 0.509 GHz are presented in column I from [5] and the ones scaled to 1 GHz are in the column II. The next step of cavity modification in order to reduce *R/Q* of the cavity is the increase of the storage cavity volume (column III). For example, if the storage cavity dimensions are increased up to approximately the same values as there were before the scaling from 0.509 to 1 GHz, the *R/Q* value of the cavity is decreased by approximately factor 8 since most of the energy (90%) is located in the storage cavity. RF voltage per cavity remains the same. This reduction in *R/Q* of the cavity is more than enough for our purpose. In fact, in our case, an intermediate modification of the storage cavity is chosen to have comfortable voltage per cavity V_0 = 319 kV. This gives the number of cavities to be 16 and the corresponding R_0/Q = 2.1 Ω per cavity. The second step can also be done by modifying the coupling between the accelerating and storage cavities which increases the stored energy in the storage cavity keeping RF voltage the same in the accelerating cavity. An appropriate combination of these two alternatives is probably the best choice and deserves further investigations.

Finally, the complete set of parameters of the RF system is calculated and summarized in Table 3. In addition, the parameters of the KEK-B LER RF system [5], which is based on ARES cavities, are presented for comparison.

Table 3: Parameters of the baseline RF system at 1 GHz and the KEK-B LER RF system from [5]

	CLIC DR	**KEK-B LER**
RF frequency [GHz]	1	0.509
Total stored energy [J]	61.2	106
Total *R/Q*: [Ω]	33.8	148
RF voltage per cavity: V_0 [kV]	319	500
Number of cavities	16	20
R_0/Q per Cavity: [Ω]	2.1	7.4
Q-factor	120000	110000
Total wall loss power [MW]	3.2	3.1
Average beam power [MW]	0.6	4.5
Total RF power [MW]	3.8	7.6
Number of klystrons	8	10
Required klystron power [MW]	> 0.5	> 0.8
Total length of RF system [m]	32	50
Bunch phase modulation peak-to-peak [deg]	0.3 (train 22%)	3.5 (gap 5%)

CONCLUSIONS

In summary, the baseline solution for the CLIC DR RF system is close to what is already in operation for many years (KEK-B, etc.). There are no feasibility issues or showstoppers. The final cavity design for both RF and mechanical aspects are still to be done to finalize the parameters of the RF system. There are several alternative solutions both at 1 and at 2 GHz which have been considered elsewhere [2] and which can improve the baseline but require more R&D effort before being adopted as a baseline.

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