TWO-FREQUENCY BEAM-LOADING COMPENSATION in the DRIVE-BEAM ACCELERATOR of the CLIC TEST FACILITY

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Abstract

The CLIC Test Facility (CTF) is a prototype two-beam accelerator, in which a high-current "drive beam" is used to generate the RF power for the main-beam accelerator. The drive-beam accelerator consists of two S-band structures which accelerate a bunch train with a total charge of 500 nC. The substantial beam loading is compensated by operating the two accelerating structures at 7.81 MHz above and below the bunch repetition frequency, respectively. This introduces a change of RF phase from bunch to bunch, which leads, together with off-crest injection into the accelerator, to an approximate compensation of the beam loading. Due to the sinusoidal time-dependency of the RF field, an energy spread of about 7% remains in the bunch train. A set of idler cavities has been installed to reduce this residual energy spread further. In this paper, the considerations that motivated the choice of the parameters of the beam-loading compensation system, together with the experimental results, are presented.

1 THE CLIC TEST FACILITY II

CTF II [1] is an experimental facility of the Compact LInear Collider (CLIC) study dedicated to demonstrate the feasibility of the CLIC two-beam accelerator scheme and its associated 30 GHz technology [2]. A high-current drive-beam generates the 30 GHz power, while the main beam probes the accelerating field in the 30 GHz accelerator. Some operational parameters of the drive-beam injector are presented in Table 1.

The drive beam is generated by an S-band RF-photo-injector whose photo-cathode is illuminated by a short pulse (8 ps FWHM), UV laser. Two S-band, disk-loaded accelerating structures are used to provide acceleration to about 35 MeV. Since efficient 30 GHz power production requires short bunches, a magnetic chicane, together with optimised phasing in the accelerating structures, is used to compress the bunches to 5 ps FWHM. After bunch compression, the beam is injected into the 30 GHz decelerator where a part of its energy is converted into 30 GHz power.

2 BEAM-LOADING COMPENSATION

The CTF drive-beam train of 500 nC during 16 ns extracts 1 GW of power from the 3 GHz accelerating structures. The related energy has to be provided by the energy stored in the structures and the heavy beam-loading has to be compensated. In the case of more moderate beam-loading, its compensation is provided by dedicated structures tuned at a frequency higher and lower than the bunch repetition frequency, while normal accelerating structures are used for acceleration [3]. In the CTF case, the drive beam accelerator has to provide both acceleration and beam-loading compensation.

Beam-loading compensation can be obtained with a single accelerating structure operated at a frequency slightly higher than the bunch repetition frequency and by injecting the first bunch of the train before the crest. This produces a phase advance along the train, i.e. the successive bunches arrive closer to the crest than the previous ones, experiencing a higher accelerating field which approximately compensates the beam-loading.

In the CTF II, simultaneously to acceleration and beam-loading compensation, the drive beam injector has to provide a way to establish the proper single-bunch energy-phase correlation required for magnetic bunch compression.

The single-bunch energy-phase correlation can be controlled by using two accelerating structures, one operated at a frequency higher and the other at a frequency lower than the bunch repetition frequency. By running the two accelerators at the same field amplitude and injecting the train at opposite phase, the single-bunch energy spread introduced in the first structure is compensated by the second one. However, by using the correct phasing and a reduction of the field amplitude in the second structure, it is possible to introduce the same energy-phase correlation in all bunches.

Table 1: Operational Parameters of the Drive-Beam Injector during 1998

Number of bunches	48
Bunch spacing	10 cm
Bunch train charge	500 nC
Energy	35 MeV
Accelerating Field	36 MV/m
Total loss factor	13.7 V/pC
Beam line energy acceptance	14%
Residual train energy spread	~ 7%
Correlated single bunch energy spread	~ 7%
Bunch length after compression(FWHM)	5 ps

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2.1 Theory

The energy gain of the *i-th* bunch (ΔT_i) of a bunch train in an accelerating structure operated at a frequency ν_1, is:

$$\Delta T_i = E_1 L \cos\left(2\pi \frac{\nu_1}{\nu_b}(i-1) + \phi_1\right)$$
$$- 2k_o q_b \left(\frac{1}{2} + \sum_{j=1}^{i-1} \cos\left(2\pi \frac{\nu_1}{\nu_b} j\right)\right) \quad (1)$$

where E_1 is the structure mean field, L is the structure length, ν_b is the bunch repetition frequency, ϕ_1 is the launching phase of the first bunch of the train into the accelerator, k_o is the beam loss factor ($k_o = \omega \, r'L/4Q$) and q_b is the bunch charge. Eq. 1 can be written as a function of the accelerator off-frequency ($\Delta\nu = \nu_1 - \nu_b$), and the sum can be written in a closed form:

$$\Delta T_i = E_1 L \cos(2\psi(i-1) + \phi_1) - k_o q_b \frac{\sin(2\psi(i-1/2))}{2\sin(\psi)} \quad (2)$$

where $\psi = \pi \Delta\nu/\nu_b$. In Eq. 2 the bunch number index i can be treated as a continuous variable. By introducing a continuous variable t to represent the time relative to the bunch centre, Eq. 2 can be modified to represent also the energy of bunch slices at time t. The energy-phase correlation of the *i-th* bunch is then given by: $\omega^{-1} d/dt \, \Delta T_i$.

The two accelerating structures of the CTF drive beam injector allow four free parameters, i.e. fields and phases (E_1, E_2, ϕ_1 and ϕ_2), which allow the fulfilment of four conditions: minimum energy spread and equal energy-phase correlation along the train, maximum energy gain and achievement of the desired amount of correlation. The requirement of minimum energy spread and of equal correlation can be expressed mathematically by requiring both bunch energy and correlation to be independent of the bunch number in the middle of the train:

$$\left|\frac{d}{di}\Delta T_i\right|_{i=\frac{N+1}{2}} = 0 \quad \text{and} \quad \left|\frac{d}{di}\left(\left(\frac{d}{dt}\Delta T_i\right)\right|_{t=0}\right|_{i=\frac{N+1}{2}} = 0 \quad (3)$$

where the derivative is taken with respect to the bunch number index i, and N is the number of bunches in the train. As a result, the phase and the field of the second accelerator (ϕ_2 and E_2, respectively) are expressed as a function of the phase and the field of the first accelerator (ϕ_1 and E_1, respectively), and of the off-frequency $\Delta\nu$:

$$\phi_2 = \alpha + \text{atg}\left[\text{tg}(\alpha + \phi_1) + \frac{2k_o q_b}{E_1 L}\frac{\cos(\beta)}{\sin(\beta)\cos(\alpha + \phi_1)}\right]$$

$$E_2 = E_1 \frac{\cos(\alpha + \phi_1)}{\cos(\alpha - \phi_2)}$$

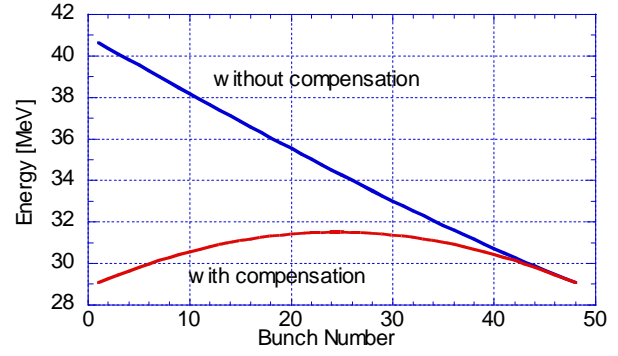where $\alpha = \pi (\Delta\nu/\nu_b)(N-1)$ and $\beta = \pi (\Delta\nu/\nu_b) N$.

Fig. 1: Bunch energy gain along the train.

To maximise the energy gain, E_1 is set to the maximum value that can be achieved. Then the choice of ϕ_1 sets the amount of energy-phase correlation. In the case of the CTF II, for $E_1 = 36$ MV/m and a required correlation of 1% per degree of bunch phase extension, ϕ_1 is -60°, ϕ_2 is +25°, E_2 is 29 MV/m, and the train energy gain is about 30 MeV. The residual energy spread is about 7%.

The train energy profile after acceleration is shown in Fig. 1 as a function of the bunch number. Also shown is the energy gain without beam-loading compensation. The beam-loading compensation scheme reduces the energy gain of the train head so that the total energy spread is reduced to about 7%.

The ratio between the residual energy spread and the energy gain in the accelerating structures depends only on the accelerator off-frequency and on the train length. In the case of the CTF II, $\Delta\nu = 7.81$ MHz, and $N = 48$, the relative energy spread is about 7% of the energy gain in the two accelerators.

2.2 The choice of the accelerator off-frequency

Together with the bunch train length, the choice of the frequency difference between the accelerating structures and the gun ($\Delta\nu$) determines the bunch train residual energy spread, the energy gain after beam-loading compensation and the versatility of the beam-loading compensation scheme. The frequency difference is then chosen to minimise the residual train energy spread and to maximise the bunch energy gain in the structures.

The train residual energy spread and the maximum energy gain as a function of $\Delta\nu$ in the case of the design parameters of the CTF injector are shown in Fig. 2. The maximum energy gain increases with $\Delta\nu$ and reaches a plateau at about 6 MHz, a larger $\Delta\nu$ does not lead to an appreciable additional energy gain. On the contrary, the residual energy spread increases more than linearly with $\Delta\nu$. However, for a given final energy and for a given bunch charge, the accelerator field required by the beam-loading compensation scheme scales inversely with $\Delta\nu$. In other words, a higher $\Delta\nu$ allows beam-loading compensation with a lower accelerating field, at the expenses of a higher residual train energy spread.
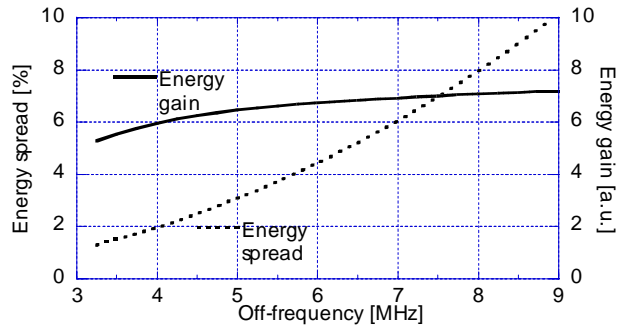
Fig. 2: Fractional energy spread [%] and maximum energy gain [a.u.].

2.3 Hardware

In CTF II, the possible choice of the accelerator off-frequency was limited to either 5 or 7.81 MHz by engineering constraints related to the timing system. The higher off-frequency has been chosen to obtain a more flexible beam-loading compensation system, effective for several combinations of bunch charges and accelerator fields.

Two special accelerating structures optimised for high-charge acceleration have been constructed at LAL, Orsay [4]. They are tuned at ± 7.81 MHz with respect to the bunch repetition frequency, they have a large iris aperture and they have been optimised for a low r'/Q (2200 Ω/m) to maximise the stored energy.

2.4 Operation

The installation of the beam-loading compensation system has been completed at the beginning of 1998. Despite the fact that the accelerating structures have been conditioned to only 36 MV/m instead of the design value of 60 MV/m, the beam-loading compensation system worked as predicted by the theory. Its flexibility allowed operation at high current levels, which enabled demonstration of the two-beam accelerator scheme [1].

Fig. 3 shows a longitudinal phase-space image of a 24 bunch train with a total charge of 120 nC. The measurement has been taken with a streak camera from a transition radiation screen in a spectrometer behind the accelerators. Only 24 bunches are shown because of the limited acceptance of the streak-camera.

Due to the gradients available to date in the accelerating structures, the single-bunch energy-phase correlation has been controlled by varying the injection phase of the train in the two accelerators, without lowering the field of the second one. This contradicts the prescription of the beam-loading compensation scheme (see Eq. 3) but produces the two-fold advantage of increasing the bunch train energy gain and of introducing a higher correlation in bunches in the bunch train tail. The latter contributes to obtaining equal bunch lengths along the bunch train, as late bunches are longer
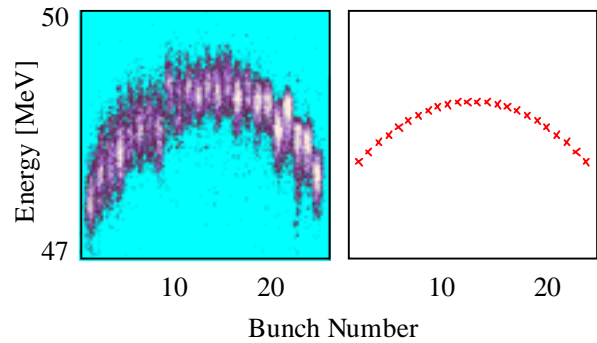

Fig. 3: Longitudinal phase space with beam-loading compensation. Left side: measured; right side: predicted.

due to the beam-loading in the RF gun.

3 IDLER CAVITIES

To further reduce the train residual energy spread, a pair of 3-cell idler cavities has been constructed at the Alfvén Laboratory, KTH, Stockholm [5]. The cavities are tuned at frequencies 31.2 MHz higher and lower than the bunch repetition frequency. Due to this frequency difference, the beam-loading is maximum in the middle of the train and vanishes for the first and last bunch. This way, the energy of the central part of the train is lowered and the residual energy spread is further decreased. The idler cavity geometry has been optimised to reduce the train energy spread to less than 3% at the nominal charge. This is of the same order of the energy spread expected from high order modes. First tests of the idler cavities with beam are foreseen for spring 1999.

4 CONCLUSION

The high transient beam-loading of the CTF drive beam ($<I> = 30$ A during 16 ns) has been compensated by adopting a two-frequency beam-loading compensation system. In addition to providing acceleration, the system reduced the total energy spread to 7% and allowed the establishment of single-bunch energy-phase correlation of the order of 1% per degree of bunch phase extension.

5 REFERENCES

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