

SECOND ORDER BEAM-LOADING COMPENSATION IN THE DRIVE-BEAM ACCELERATOR OF THE CLIC TEST FACILITY

M.Valentini, INFN & Università, Milano, Italy

H.Braun, CERN, Geneva, Switzerland

S.Rosander, Alfvén Laboratory, KTH, Stockholm

Abstract

The CLIC Test Facility (CTF) is a prototype two-beam accelerator, in which a high-current “drive beam” together with deceleration structures is used to generate the RF for the main beam accelerator. The high transient beam-loading of the CTF drive-beam linac is partially compensated for by adopting a two-frequency beam-loading compensation system. The drive beam energy distribution after acceleration has a parabolic profile with the leading and trailing bunches having the same energy and the central ones having a higher energy. A pair of idle cavities has been installed and used to reduce this residual energy spread further. The idle cavities are tuned at frequencies 31.2 MHz higher and lower than the bunch repetition frequency. In this way the beam-loading of the individual drive-beam bunches is at its maximum in the middle of the 48 bunch train, and it is 90° out of phase for the last bunch. As a result, the energy spread is further decreased. The use of two cavities allows to conserve the energy-phase correlation of individual bunches. In this paper, the considerations which motivated the choice of the parameters of the idle cavities are presented, and the experimental results discussed.

1 THE CLIC TEST FACILITY II

The CLIC Test Facility II (CTF II) [1] is a prototype two-beam accelerator 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.

Table 1: Operational Parameters of the drive-beam Injector during 1999

| | |
|--|-----------|
| 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 after 1 st order beam-loading compensation | ~ 7% |
| Correlated single bunch energy spread | ~ 7% |
| FWHM bunch length before compression | 10 ps |

Some operational parameters of the drive-beam injector are presented in Table 1.

The drive-beam accelerator consists of two S-band structures which accelerate a bunch train of 48 bunches with a total charge of about 500 nC during 16 ns. The latter extracts about 1 GW of instantaneous power from the 3 GHz accelerating structures. This is far more than the power input to the accelerators. The related energy has to be provided by the energy stored in the structures and the heavy beam-loading has to be compensated.

The effect of this substantial beam-loading is compensated for by using the two-frequency beam-loading compensation scheme described in [3]. In this scheme, the two accelerating structures are operated 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. The drive beam energy distribution after acceleration has a parabolic profile with the leading and trailing bunches having the same energy and the central bunches having a higher energy. The two-frequency beam-loading compensation scheme provides a way to establish the proper single-bunch energy-phase correlation required for magnetic bunch compression. 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. A detailed description of the beam-loading compensation system and of the hardware used is given in [3] and in its references.

2 IDLE CAVITIES

To further reduce the train residual energy spread, a pair of 3-cell idle cavities has been constructed at the Alfvén Laboratory, KTH, Stockholm. The cavities are tuned at frequencies 31.2 MHz higher and lower than the bunch repetition frequency. Due to this frequency difference, the voltage induced by the individual drive beam bunches does not add in phase along the train.

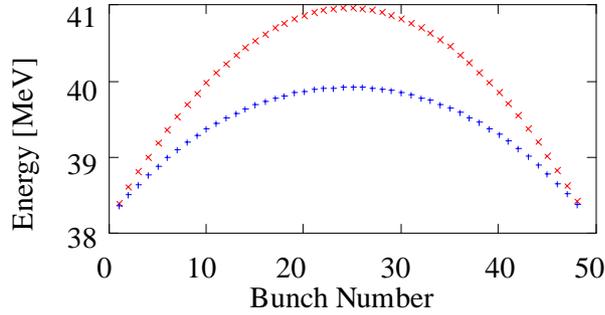


Figure 1: Energy distribution along the bunch train with (+) and without (x) the idle cavities.

The total voltage is maximum in the middle of the 48 bunch train, and it is 90° out of phase for the last bunch. This way, the energy of the central part of the train is lowered while the first and last bunch experience only their own wake. As a result, the residual energy spread is further decreased. The idle cavity design has been optimised to reduce the train energy spread to less than 3% at the nominal charge, which is of the same order of the energy spread expected from higher order modes. Figure 1 shows the energy distribution with and without the idle cavities for a bunch-train charge of 400 nC. The total energy spread is reduced to less than 4%.

The use of two cavities tuned at 31.2 MHz above and below the bunch repetition frequency allows to conserve the energy-phase correlation within individual bunches.

2.1 Design Parameters of the Idle Cavities

As the bunch length after acceleration is shorter than 10 ps (FWHM), while the idle cavity resonant period is about 333 ps, the bunches can be regarded as infinitely short. Thus the deceleration of the n -th bunch in the idle cavities can be written as:

$$-\Delta W_n = 2k_0q \left\{ \frac{1}{2} + \sum_{m=1}^{n-1} \cos \left(2\pi \frac{\Delta f}{f_b} m \right) \right\} \quad (1)$$

where q is the bunch charge, Δf is the frequency difference between resonant frequency, f_0 , and bunch repetition frequency, f_b , and the loss factor, k_0 , is $k_0 = R/Q \cdot \omega/4$, where R is the shunt impedance (linac convention), Q is the quality factor and $\omega = 2\pi f_0$. By writing the summation in closed form, Equation (1) reads:

$$-\Delta W_n = k_0q \sin \left((2n-1)\pi \frac{\Delta f}{f_b} \right) / \sin \left(\pi \frac{\Delta f}{f_b} \right) \quad (2)$$

This expression has the same value for the last and for the first bunch, i. e. $-\Delta W_{48} = -\Delta W_1$, for $\Delta f = \pm 31.23$ MHz and so the idle cavity frequencies were chosen 2967.32 and 3029.78 MHz, respectively. It is interesting to note that the necessary off-frequency, Δf , depends only on the number of bunches in the bunch train and not on the beam intensity. This has the unavoidable consequence that the effectiveness of the idle cavities is limited to the operation at the design bunch train length.

Table 2: Idle cavity design and measured parameters

| | High frequency | | Low frequency | |
|-----------------|------------------|------------------|------------------|------------------|
| | Design | Measured | Design | Measured |
| Frequency [MHz] | 3029.78 at 30 °C | 3030.09 at 23 °C | 2967.32 at 30 °C | 2967.72 at 23 °C |
| R/Q [Ω] | 425 | 490 ± 30 | 425 | 475 ± 30 |

On the other hand, the drive beam intensity does determine the level of compensation introduced by the idle cavities and it is clear from Eq. (2) that the deceleration scales linearly with the bunch charge.

From Equation 2 it is clear that in order to obtain full compensation of the residual 7% energy spread for the typical operation conditions presented in Table 1, a total loss factor $k_0=8$ V/pC is required. The latter corresponds to a total R/Q of the idle cavities of 1700 Ω. In order to allow operation at bunch train charges higher than 500 nC, it has been decided to limit the compensation level and to accept a residual energy spread of 3-4% for a bunch train charge of 500 nC. This corresponds to a total loss factor of 4 V/pC and to a total R/Q of 850 Ω. The nominal and measured parameters at the operational temperature of 30 °C are reported in Table 2.

2.2 Construction and test of the idle cavities

A pair of 3-cell OFHC copper cavities were designed, constructed and tested at the Alfvén Laboratory with dimensions according to URMEL calculations performed at CERN. The cavity geometry is shown in Figure 2, the high frequency cavity is on the left side (i.e. the three far left cells) and the low frequency cavity on the right (i.e. the three far right cells).

The individual cells are tuned for having the π -mode at the nominal frequency with equal field amplitudes in the cells [4]. This has been confirmed by cold-tests. After pre-trimming and brazing of the cavity cells, only a slight change of the cell gap lengths remains in order to finally set the cell frequencies. This was done by moving the partition walls of the cavity assembly into position with an expandable special tool.

The measured parameters (at 23°C) of the idle cavities are presented in Table 2. The cavities match well the design specifications. The R/Q values were found via perturbation technique measurement of the electric field on axis [5].

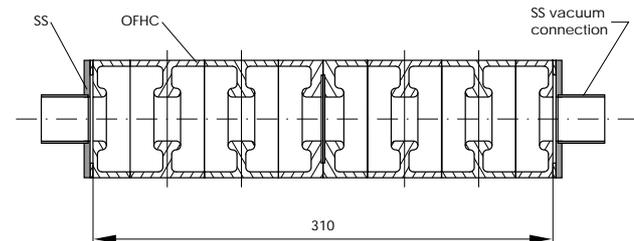


Figure 2: Idle cavity cross section.

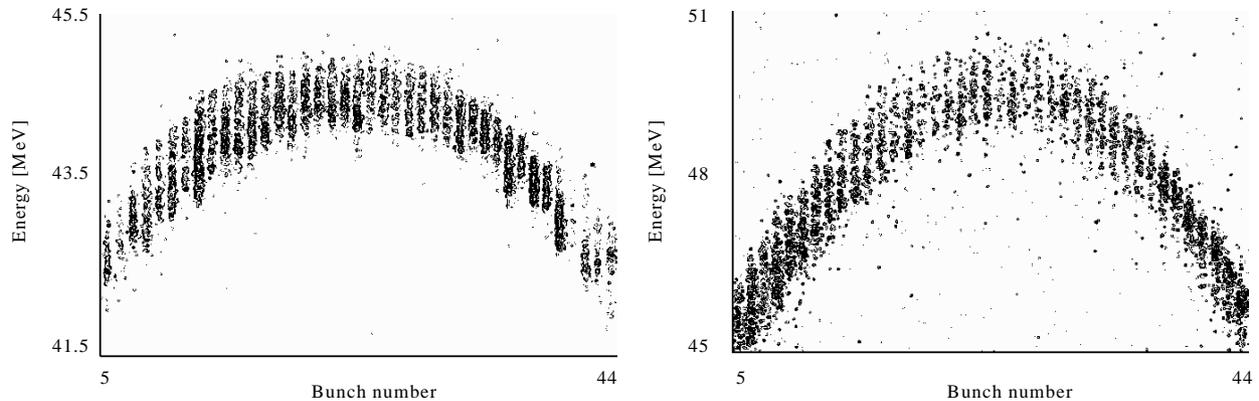


Figure 3: Longitudinal phase space after the installation of the idle cavities. Left: drive beam charge 200 nC, residual energy spread 5.9%. Right: drive beam charge 50 nC, residual energy spread 7.2%.

3 OPERATION

The installation of the beam-loading compensation system has been completed at the beginning of 1998 and the idle cavities have been installed at the beginning of 1999. Despite the fact that the 3 GHz 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].

Figure 3 shows the longitudinal phase space of the bunch train after the installation of the idle cavities in case of a train charge of 200 and 50 nC, respectively. The longitudinal phase space has been measured with a streak camera from a transition radiation screen in a spectrometer behind the accelerators. This way the energy spread is translated in position spread. Only the central part (i.e. 40 bunches) of the bunch train is visible, due to the limited acceptance of the streak camera. As expected, the residual energy spread decreases as a function of the bunch train charge.

The measurements are compared with the predictions of the above-reported analytical calculations in Table 3. It is clear that the energy spread reduces with increasing charge as predicted. In addition, there is a very good agreement between measurements and predictions. Without the idle cavities one would expect for the CTF II beam-loading compensation scheme that the energy spread is more or less constant at ~7%.

In terms of beam performance, the installation of the idle cavities enabled the transmission of 23% more drive beam charge through the 30 GHz decelerator in comparison with the previous performance. However, in the present CTF II set-up, the drive beam decelerator is twice as long as before, i. e. the improved transmission is gained despite increased demands.

The idle cavities did not cause any problems with vacuum, electrical break-downs or transverse wakefields.

Table 3: Idle cavities performance

| Drive Beam Charge [nC] | Measured $\Delta E/E$ [%] | Expected $\Delta E/E$ [%] | Peak Field [MV/m] |
|------------------------|---------------------------|---------------------------|-------------------|
| 400 | 4.3 | 4 | 7 |
| 200 | 5.8 | 5.5 | 3.5 |
| 50 | 7.4 | 6.3 | 0.8 |

4 CONCLUSION

The beam-loading compensation system of the CTF II has been completed with the installation of the idle cavities. In addition to providing acceleration, the system reduces the total energy spread to a few percent and allows the establishment of a single-bunch energy-phase correlation of the order of 1% per degree of bunch phase extension. The idle cavities performed as predicted and reduced the residual drive beam energy spread depending on the bunch charge. The installation of the idle cavities enabled the transmission of 23% more charge through the 30 GHz decelerator.

REFERENCES

- [1] H.H. Braun for the CTF team, "Experimental Results and Technical Research and Development at CTF II", this conference.
- [2] J.P. Delahaye and 26 co-authors, "CLIC, a Multi-TeV e^\pm Linear Collider", workshop on Development of Future Linear e^\pm Colliders for Particle Physics Studies, Lund, 1999 and CLIC note 420.
- [3] M.Valentini, H.H.Braun, "Two-frequency beam-loading compensation in the drive-beam accelerator of the CLIC Test Facility", PAC '99 (1999) 3402.
- [4] D.E. Nagle, E.A. Knapp, and B.C. Knapp, "Coupled Resonator Model for Standing Wave Accelerator Tanks", Rev. Sci. Inst. 38, No. 11 (Nov. 1967) 1583
- [5] See e. g. E.L. Ginzton, "Microwave Measurements", p.435 ff., McGraw Hill 1957