

# Multi-frequency Acceleration for the CLIC Drive Linac with Beam Loading and HOM Compensation

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## Abstract

In previous CLIC drive linac designs four trains spaced by 2.84 ns of 11 to 43 bunchlets (1 cm bunchlet spacing) were foreseen to produce via the transfer structures 30 GHz power pulses (~ 160 MW/m) to fill the accelerating structures of the main linac. Since the trains are spaced by 2.84 ns it is foreseen that a fundamental accelerating frequency of  $1/2.84 \text{ ns} = f_0 = 352 \text{ MHz}$  together with its harmonics will be used to obtain a repetitively equal treatment of all four trains. Reference [2] gives the recent results of two optimized zero beam current flat tops for 22 bunchlets lasting  $90^\circ$  at 352 MHz. In the following we consider the three **individual optimizations** of fundamental frequency, second and fourth harmonic cavities for the synthesis of the above flat tops, the main problems being the beam loading compensation and the HOM parasites.

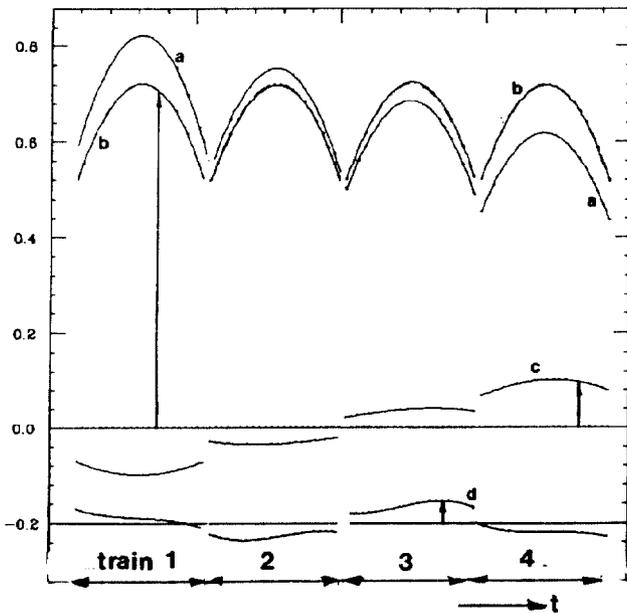


Figure 1. Decrease of normalized accelerating voltage due to beam loading over four trains of 22 bunchlets (upper full trace a). Only the short phase intervals (of  $90^\circ$ ) populated by the 22 bunchlets are shown whereas the remaining **unpopulated**  $270^\circ$  in each of the 4 periods **have been cut out**. The upper indented branch shows the ideal cosine accelerating voltage. This branch is almost covered by the resulting beam loading compensated curve b. Curve c shows the compensating voltage obtained as a fast beat between the two groups of compensating cavities with  $\mu = 0.09$ . The compensation causes a net acceleration reduction of 28%. Curve d shows the error curve magnified by 10. The r.m.s. error with respect to the ideal curve is 0.0025. (No HOMs included.)

## 1. BEAM LOADING COMPENSATION FOR FUNDAMENTAL FREQUENCY CAVITIES

The passage of a bunchlet of charge  $q$  (80 nC) creates in each cavity a normalized (with respect to the peak accelerating field  $U_0$ ) real negative loading phasor of:

$$U = -q\omega(R/Q)U_0^{-1}, \quad (1)$$

where  $R/Q = 136 \Omega/\text{m}$  (circuit convention) for the fundamental frequency in a LEP 200 superconducting (SC) cavity. Furthermore the peak accelerating field  $U_0$  is assumed to be 6 MV/m for the fundamental and the  $H = 2$  cavities. The  $H = 4$  cavity at 1.4 MHz has an assumed peak field of 10 MV/m (CEBAF value).

As the loading phasors tend to accumulate destructively in the fundamental frequency cavities, the net acceleration will decrease from train to train (see Fig. 1, trace a). The remedy used in the following to obtain almost the same acceleration for all four trains is to add to the large group of cavities at 352 MHz two small subgroups of equal length with different frequencies:

$$f_0(1 - \mu) \quad \text{and} \quad f_0(1 + \mu)$$

where  $f_0 = 352 \text{ MHz}$ , having phases such that the two subgroups of cavities decelerate the first train strongly then the second weakly. The third train is weakly accelerated and the fourth strongly (See Fig. 1 trace c). Obviously, this equalization is obtained at the expense of some net acceleration.

## 2. ACCELERATION OF 22 BUNCHLETS WITH HOMs (FUNDAMENTAL FREQUENCY)

The excitation of HOMs by the passage of bunchlets also takes place according to exp. (1) but this time the HOMs' ( $R/Q$ )s should be used and the starting condition is zero field at the arrival of the first bunchlet.  $R/Q$  values for the four lowest HOMs of a single LEP 200 cavity with transition pieces to 100 mm diameter [3], used in the following calculations, are listed below:

Frequency [MHz]	$R/Q$ [ $\Omega/\text{m}$ ] (circuit convention)
352.9	136 (fundamental)
637.3	14.2
641.2	33
1 002.7	9.1
1 155.8	5.1

### 3. HARMONIC (PERIODIC) HOM VOLTAGES THROUGH COMBINED PREEXCITATION AND BEAMLOADING.

Any existing HOM will during one fundamental period perform in the complex plane  $F_{HOM} = f_{HOM}/f_0$  turns.

The missing (or excess) angle with respect to an integral number of turns  $N$  (as required for the HOM voltage to be periodic) is given by

$$\varphi = 360 \cdot (F_{HOM} - N)$$

The sum of the beamloading phasors of 22 bunchlets inside a HOM at the time corresponding to the passage of the train centre can be presented by a real phasor of amplitude:

$$B = -q\omega(R/Q)U_0^{-1} \sum_{M=-10}^{+11} \text{EXP}(2\pi j(M - 0.5)/K)$$

where  $K = 86$  (number of bunchlet periods per train period; whereof only 22 are populated).

If we choose the integral number  $N$  nearest to  $F_{HOM}$  such that  $|\varphi|$  is less than or equal to  $180^\circ$ , then we can by preexciting the HOM with a particular phase and amplitude  $P_0$  obtain periodicity by simple addition of the beamloading phasor  $B$  to the phasor  $P_e = P_0 \cdot \text{EXP}(2j\pi F_{HOM})$ . ( $P_e$  is  $P_0$  one period later):

$\varphi < 0$ ; the phase must be increased:

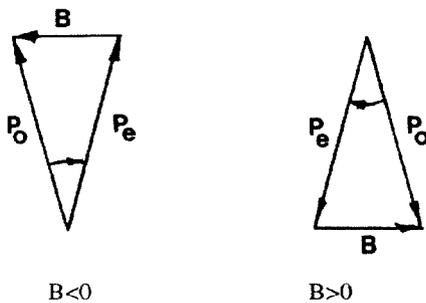


Figure 2. Example of preexcited HOM phasor  $P_0$  at the beginning of the train and  $P_e$  at the end of the train period and the beamloading phasor  $B$ . All phasors are shown at the time corresponding to the passage of the middle of the train.

The above diagram demonstrates the possibility of advancing the HOM phase with neg.  $\varphi$  (for retarded phases with positive  $\varphi$  there is a similar solution) to obtain  $2\pi N$  phase advance per train period by addition of the beamloading phasor  $B$ . A periodic HOM voltage is imposed. One can now either modify or cancel it (in most cases only partially) with the fundamental voltage to suit the specified cavity purpose for all four trains.

To avoid excessive preexcitation amplitudes, the HOM preexcitation being proportional to  $1/\sin(\varphi/2)$ , no preexcitation is applied when  $|\varphi|$  is smaller than  $18^\circ$ .

Furthermore, the preexcitation offers the advantage that, although there is energy exchange between bunchlets via the HOM inside one bunchlet train, there is *no net energy ex-*

*change* averaged over one train for the obvious reason that the initial HOM amplitude is restored after the passage of each train.

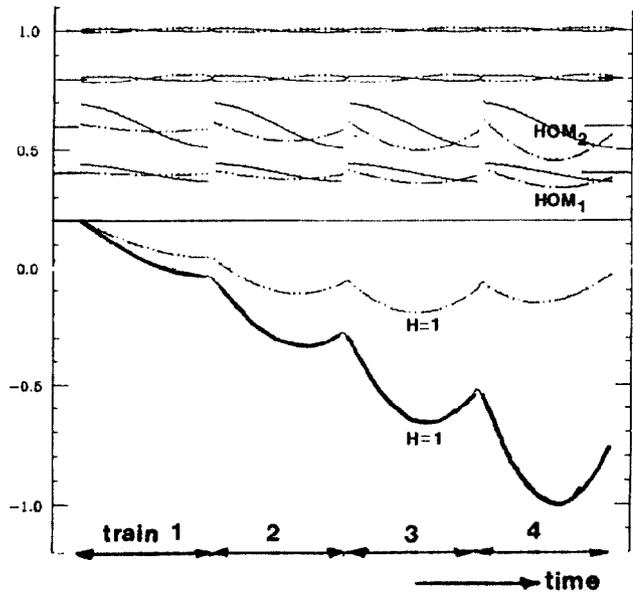


Figure 3. Beam excited fundamental (two lower traces) and HOM voltages (full line: main cavities, dashed lines: compensation cavities) with preexcitation and reoptimisation. Periodic HOM voltages are obtained (except for  $HOM_1$  and  $HOM_2$  of the compensation cavities, where  $|\varphi|$  is smaller than  $18^\circ$ ). The r.m.s. error is reduced from 0.019 to 0.004.

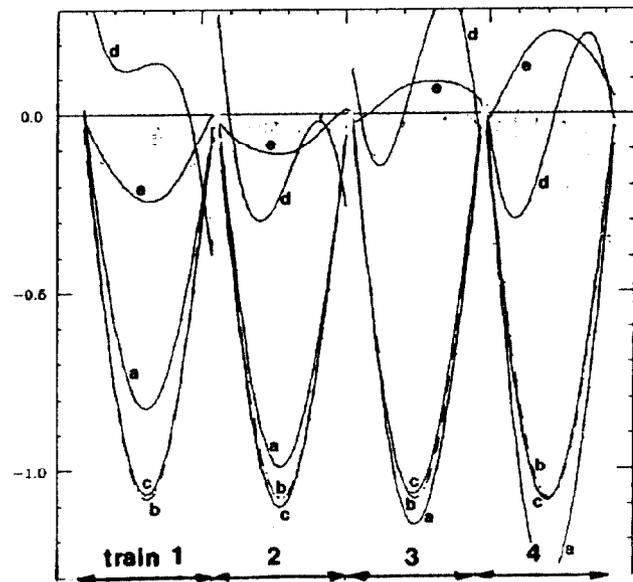


Figure 4. Increase of normalized decelerating voltage due to beamloading (lower full trace a). The lower indented trace b shows the ideal cosine voltage almost covered by the full trace c representing the obtained compensated voltage. (The preexcited HOMs are included.) The beamloading compensation is given by trace e and the deviation with respect to the ideal cosine by trace d. (magnification 10). The r.m.s. error is 0.019.

At the nominal 1.7 kHz pulsing rate the required mean RF power is 39.7 kW/m for the main structures and 7.2 and 4.1 kW/m for the low and high frequency compensation ones respectively ( $\mu = 0.093$ , total length of compensation cavities = 14.3%). The non-preexcited HOMs 1 and 2 of the high freq. compensation cavities ( $|\phi| < 18^\circ$ ) yield 11 and 27 W/m respectively.

#### 4. SECOND HARMONIC CAVITIES (SCALED FROM LEP200 SC CAVITIES)

Beamloading and HOM compensation are obtained in a similar way to that for  $H = 1$ . Note that  $H = 2$  cavities are required with a decelerating phase; their amplitude is increased (by the four trains by  $\approx 5$  MV/m). To avoid excessive final voltages an initial peak accelerating voltage of only 6 MV/m was assumed. Fig. 4 gives the result of an optimisation.

At the nominal 1.7 kHz pulsing rate the yielded mean RF power is 65.8 kW/m for the main structures and 0.8 and 4.1 kW/m for the low and high frequency compensation ones respectively ( $\mu = 0.0647$ , total length of compensation cavities = 25.5%).

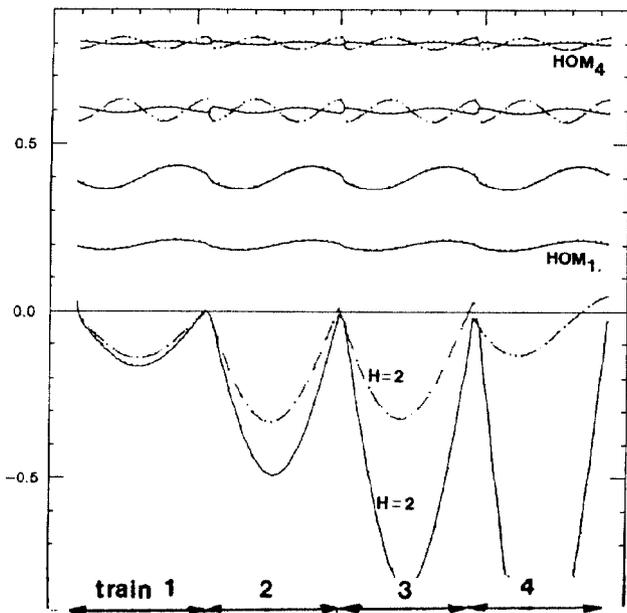


Figure 5. Beam excited fundamental and HOM voltages versus time (unpopulated phase intervals are omitted). The full curves represent voltages in the main group of cavities (magnified by 2) the indented ones the summed voltages of the two compensation groups (magnified by 5). The HOM voltages include the calculated preexcitation values. Traces are separated by artificial vertical offsets.  $H = 2$

#### 5. FOURTH HARMONIC CAVITIES (SCALED FROM LEP 200 SC CAVITIES)

The net beamloading of each bunchlet train is zero since the train duration is one period of the fourth harmonic; no beamloading compensation cavities are foreseen.

Since beamloading and cavity fundamental phasors (at  $4 \cdot f_0$ ) turn in synchronism, it is possible by proper phasing of the cavity fundamental to obtain the specified cosine behaviour exactly (no HOMs included).

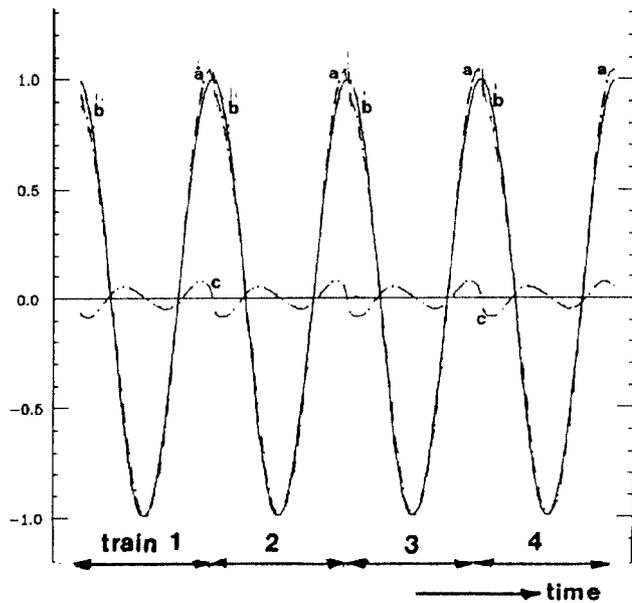


Figure 6. Result of optimization including preexcited HOMs (dotted curve a). The ideal cosine curve is given by curve b. The resulting error curve (not magnified) is labelled c. Although preexcited, the HOMs create r.m.s. errors of 4.5%.

#### 6. CONCLUSIONS

The investigations described show that in principle the acceleration at the fundamental frequency, in spite of beamloading and HOMs (only the four lowest HOMs have been taken into account), can be achieved with an error of less than 0.56% r.m.s.. That errors are 1.9% and 4.5% for the second and fourth harmonics respectively.

In the case of high precision preacceleration (with fundamental amplitude = 1, second harmonic amplitude = 0.343 and fourth harmonic amplitude = 0.025, yielding a flat top of 0.68 [2]) the r.m.s. error amounts to 1.3% of the flat top value.

For a global optimisation with respect to the flat top (and not individual optimisations of fundamental and harmonics 2 and 4) a better flat top can be expected.

It remains to be studied whether in a real drive linac the parameters of the optimisations, in particular the bunchlet intensity, can be adjusted with sufficient precision.

#### 7. REFERENCES

- [1] L. Thorndahl, "A multi-frequency preacceleration system for the CLIC drive linac with beam loading compensation", CERN CLIC Note 169.
- [2] J.P. Delahaye, "CLIC Drive Beam Generation Scheme based on FEL Bunching and RF Accelerator", CERN CLIC Note 212.
- [3] R. Baskaran, Private communication.