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CLIC-Note-697

EFFICIENT LONG-PULSE FULLY LOADED CTF3 LINAC OPERATION

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Abstract

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Presented at LINAC06, Knoxville, TN, US, August 21-25, 2006

Geneva, Switzerland
November 2006

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An efficient RF to beam energy transfer in the accelerating structures of the drive beam is one of the key points of the Compact Linear Collider (CLIC) RF power source. For this, the structures are fully beam-loaded, i.e. the accelerating gradient is nearly zero at the downstream end of each structure. In this way, about 96 % of the RF energy can be transferred to the beam. To demonstrate this mode of operation, 1.5 μs long beam pulses are accelerated in six fully loaded structures in the CLIC Test Facility (CTF3) Linac. The final beam energy is compared to the input RF power of the structures, proving the efficient energy transfer.

INTRODUCTION

CLIC is a linear e^+e^- collider optimised for a centre-of-mass energy of 3 TeV [1]. It is based on the use of normal conducting accelerating structures operated at high gradient (150 MV/m), and powered by 30 GHz high-power RF pulses. Since conventional RF sources cannot provide such pulses, the CLIC scheme relies on a two-beam-acceleration concept [2], where a high current electron beam, the so-called drive beam, will generate the RF power for the main beam. The CLIC drive beam accelerator will be operated at 937 MHz (30 GHz/32). Since power efficiency is of utmost importance for CLIC, the drive beam is accelerated in fully-loaded cavities, such that the RF power is almost completely converted to beam energy.

The CLIC Test Facility (CTF3) [3], built at CERN by an international collaboration, aims at demonstrating the feasibility of the CLIC scheme by 2010. One of the main goals of CTF3 is the validation of the CLIC drive beam generation scheme with fully loaded Linac operation.

THE CTF3 INJECTOR AND LINAC

The drive beam injector [4] comprises a thermionic gun, three 1.5 GHz sub-harmonic bunchers (SHBs), an S-band pre-buncher, a tapered phase velocity travelling-wave buncher and two S-band accelerating structures, operating at 3 GHz. Depending of the beam current an energy of about 25 MeV is achieved at the end of the injector. A magnetic chicane with collimators is then used to eliminate off-energy particles and to perform bunch compression (Fig. 1).

The CTF3 Linac is composed of 11 modules, each 4.5 m long. At present 6 modules are equipped with two accelerating structures respectively. Fig. 2 shows the CTF3 Linac up to module 10. Modules 5 to 7 contain two cavities each providing a nominal energy gain of about 7 MeV. The beam is not further accelerated in modules 8[1], 9 and 10. The beam energy can either be measured in the spectrometer lines 4 or 10, the transverse focusing is done by means of quadrupole triplets.

The 3 GHz accelerating structures consist of 32 cells plus 2 coupler cells with a total length of 1.22 m and operate in the $2\pi/3$ mode with a moderate averaged accelerating gradient of 6.5 MV/m (for the nominal beam current of 3.5 A). In order to suppress the transverse higher order modes (HOMs) the structures (called SICA [5] - Slotted Iris Constant Aperture) have four radial slots in the iris to couple out the HOMs to SiC loads. The same structure type (scaled to 937 MHz) will be used in CLIC for the drive beam acceleration. The RF power is supplied by klystron-modulators (MKS) providing power in the range of 35 MW to 45 MW.

In order to maximize the efficiency, the structures are operated in fully beam-loaded condition, meaning that all the RF power, except for ohmic losses, is transferred into beam energy. In this mode of operation, an RF-to-beam transfer efficiency of about 96 % for both, the CLIC and CTF3 structures, is expected. Fig. 3 demonstrates the principle of the fully beam-loaded operation.

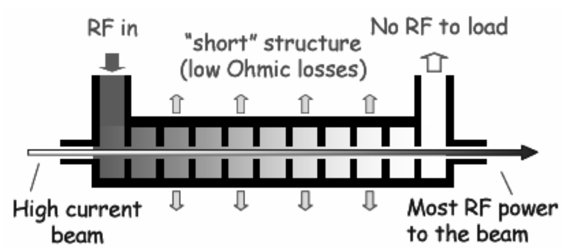

Figure 3: Principle of fully beam-loaded acceleration: A high-current long pulse extracts most of the RF power from a short travelling wave structure.

The first part of the Linac was commissioned with beam in 2003 and first studies concerning the fully loaded operation were performed [6].

THE EXPERIMENTAL SET-UP

The experiments were performed with bunches spaced by 10 cm, hence the SHBs were switched off. The RF power is in normal CTF3 operation increased by means of

[1] The beam can be deflected towards the Power Extraction and Transfer Structures (PETS) to produce 30 GHz RF power.

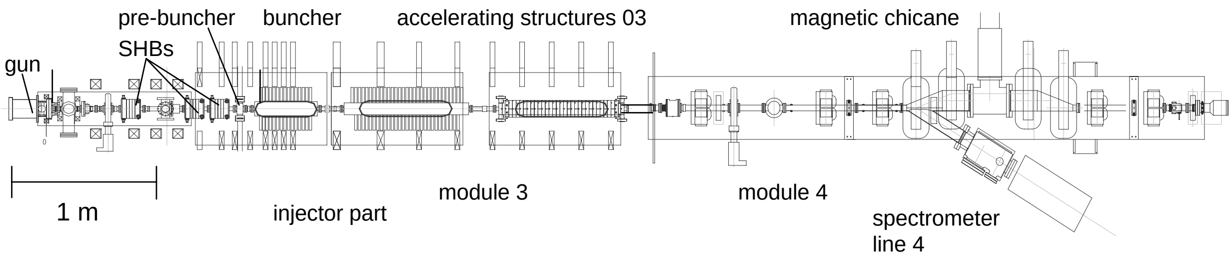

Figure 1: Layout of the CTF3 injector and the magnetic chicane.

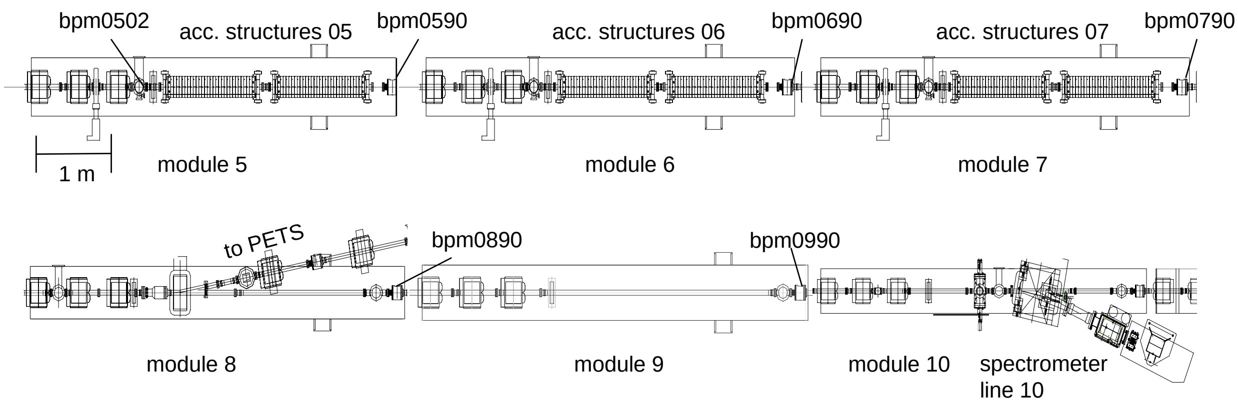

Figure 2: Layout of the CTF3 Linac up to module 10.

a RF pulse compression system to reach higher beam energies. In this mode of operation, a RF phase variation and hence an unequal energy gain along the pulse is inevitable. For CLIC, no RF pulse compression is foreseen, therefore the experiments were performed with uncompressed pulses for the structures in the Linac. To gain more energy in the injector, the pulses for the accelerating structures 03 were compressed.

In order to measure the transfer efficiency from RF-to-beam energy, the exact knowledge of the input power for all accelerating structures, the beam current and the energy gain is essential. For this purpose the beam position monitors (BPMs) were re-calibrated, thus an accuracy of ± 1 % of the beam current measurement can be assumed. The RF signals were calibrated by means of the direct beam loading signal, i.e. the energy released by the beam in an undriven cavity, which is measured at the structure output and then compared to the theoretical value.

The beam current and the RF input power and phase were then adjusted such that the fully beam-loaded condition is fulfilled, hence no RF power is measured at the output of the accelerating structures. For this, always one klystron pulse at a time was delayed after the beam pulse and the output RF and the direct beam loading signal were subsequently equalized. For about 11.8 MW input power, the fully beam-loaded condition is obtained for a 2.65 A beam current. Fig. 4 shows the beam current up to module 10. No beam losses occur along the Linac.

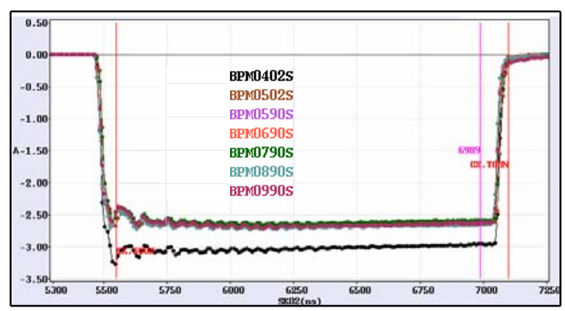

Figure 4: Calibrated BPM beam current signals up to module 10. The BPM0402 signal is acquired in front, all the others after the magnetic chicane.

To determine the transfer efficiency, the beam energy is measured in the spectrometer lines 4 and 10. However, the measurement of absolute beam energy is not precise enough to make a distinct statement about the efficiency. Therefore relative energy measurements were performed in spectrometer line 10 (time resolved). The energy was first determined for a beam accelerated in all cavities. Then always one klystron RF pulse was delayed after the beam pulse. The difference in energy is then given by both, the missing acceleration due to the RF field and the deceleration due to the direct beam loading. Since the direct beam loading is known, the contribution due to the RF can be calculated and compared to theoretical predictions.

THE EXPERIMENTAL RESULTS

Fig. 5 shows the RF signals at the structure input and the output for one accelerating cavity per module. One notes that some power goes to the load of the structure in the injector, hence they are not operated in fully beam-loaded condition. The other structure output signals entirely vanish along the steady state of the pulse. Only at the beginning and at the end of the pulse the power is not fully taken out by the beam. Integrating over the whole pulse yields an efficiency of about 98 %. These transient effects are negligible for CLIC, since the length of the drive beam pulse corresponds to 100μs.

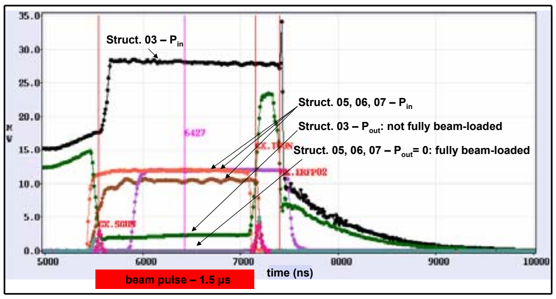

Figure 5: RF power levels at the structure input and output for always one accelerating structure per module as a function of time.

Fig. 6 shows the analog power signals for one accelerating structure demonstrating the fully beam-loaded operation. Except for the transient at the end of the pulse, the output power is zero. The output power at the beginning of the pulse was minimized by carefully adjusted beam and RF timings.

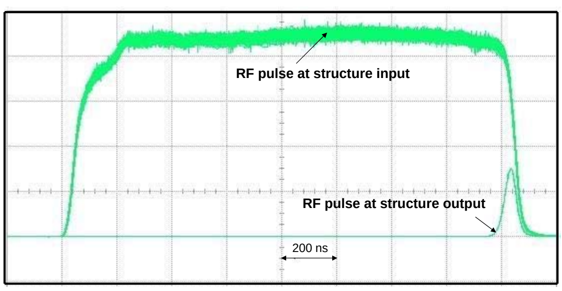

Figure 6: RF power at the structure input and output, proving that nearly all the power is taken out by the beam.

For the calculation of the RF-to-beam efficiency the steady state of the pulse was considered. Table 1 lists the theoretical energy gain per module (two structures) for the corresponding calibrated input power of the structures and the measured beam current. The results obtained from the relative beam energy measurements (the deceleration due to the direct beam loading is already subtracted) are then compared to the predicted energy gain. The accuracy for both the measured and the calculated energy gain was estimated to $\pm$ 0.1 MeV.

Table 1: Comparison of the theoretical and measured energy gain per module (two accelerating structures).

module	P_{in} [MW]	I_b [A]	ΔE_{th} [MeV]	ΔE_m [MeV]	ratio [%]
05	11.76	2.65	8.50	8.44	99.3
06	11.84	2.65	8.56	8.45	98.7
07	11.82	2.65	8.54	8.56	100.2
sum			25.60	25.45	99.4

One notes that the measurements are in excellent agreement to the theoretical energy gain per module. The total measured energy gain corresponds to 99.4 % of the predicted one. If the ohmic losses are included, the obtained RF-to-beam transfer efficiency yields 95.3 %.

For the sake of completeness, the results from the absolute energy measurements performed in spectrometer lines 4 and 10 are presented. The energy gain was measured to 24.9 MeV which is close to the theoretical value and therefore confirms the efficient energy transfer.

CONCLUSIONS

An efficient RF-to-beam energy transfer in the structures of the drive beam accelerator is of utmost importance for the CLIC project. To demonstrate this key issue, the CTF3 Linac was operated in fully beam-loaded condition. Beam current and RF input powers and phases of the structures were successfully adjusted that the output powers entirely vanished over the steady state of the pulse. The measured energy gain per module is in excellent agreement to theoretical predictions and a final RF-to-beam energy transfer efficiency of 95.3%, including ohmic losses in the structure, was measured.

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