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FIRST FULL BEAM LOADING OPERATION WITH THE CTF3 LINAC

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Abstract

The aim of the CLIC (Compact Linear Collider) Study is to investigate the feasibility of a high luminosity, multi-TeV linear e+e- collider. CLIC is based on a two-beam method, in which a high current drive beam is decelerated to produce 30 GHz RF power needed for high-gradient acceleration of the main beam running parallel to it. To demonstrate the outstanding feasibility issues of the scheme a new CLIC Test Facility, CTF3, is being constructed at CERN by an international collaboration. In its final configuration CTF3 will consist of a 150 MeV drive beam linac followed by a 42 m long delay loop and an 84 m combiner ring. The installation will include a 30 GHz high power test stand, a representative CLIC module and a test decelerator. The first part of the linac was installed and commissioned with beam in 2003. The first issue addressed was the generation and acceleration of a high-current drive beam in the "full beam loading" condition where RF power is converted into beam power with an efficiency of more than 90 %. The full beam loading operation was successfully demonstrated with the nominal beam current of 3.5 A. A variety of beam measurements have been performed, showing good agreement with expectations.

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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 upon a two-beam-acceleration concept [2]. A high current electron beam, the so-called drive beam, will be running parallel to the main beam and will be decelerated to generate the RF power.

The drive beam will be accelerated in a linac using low RF frequency. Since in a linear collider the main beams are used only once per collision, the overall efficiency is paramount. A very efficient energy transfer to the drive beam is critical. In order to obtain that, the drive linac will be operated in the " full beam loading" condition, where the beam extracts almost all the power from the structures (see Fig. 1). In this condition, an overall transfer efficiency of about 98 % is expected. This exceeds the efficiency of superconducting structures if one takes into account the cryogenic power needed for cooling.

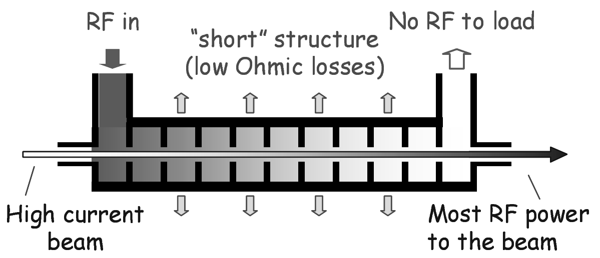

Figure 1: Principle of full loaded acceleration: a high-current long beam pulse extracts most of the RF power from a short travelling wave structure.

Subsequent manipulations transform the long drive beam pulse, with low bunch repetition frequency, into several short pulses with a high bunch repetition frequency and a correspondingly higher current. From these, the required RF power at 30 GHz can be extracted and fed into the CLIC main beam.

A new CLIC Test Facility (CTF3) is being built at CERN in order to demonstrate this drive beam generation scheme. It will also serve as a 30 GHz RF power source, necessary to develop CLIC RF components [3]. CTF3 started in 2001 and is being built, commissioned and used for testing in stages over several years until 2009. It uses the buildings of the former LEP pre-injector complex and makes maximum use of existing hardware.

The CTF3 complex is designed to work at a lower beam current and a lower energy than the CLIC RF power source (3.5 A instead of 7.8 A and 150 MeV compared to 2 GeV). In its final configuration it will consist of a 70 m long linac followed by two rings, where the bunch manipulations will be carried out: a 42 m long delay loop and an 84 m combiner ring. The installation will also include a 30 GHz high power test stand, a representative CLIC module and a test decelerator. CTF3 is built by a collaboration including CERN, INFN-Frascati, LAL-Orsay, North Western University of Illinois, RAL, SLAC, Uppsala University and Finnish industry.

Already in 2001 and 2002 preliminary experiments were carried out [4] using the modified LEP pre-injector complex. Here the principle of manipulating the beam to increase current and bunch frequency was successfully demonstrated at low current (0.3 A). Up to five bunch trains were interleaved without measurable losses. Since then, new equipment has been installed, and in June 2003 the commissioning of the first part of the new linac began.

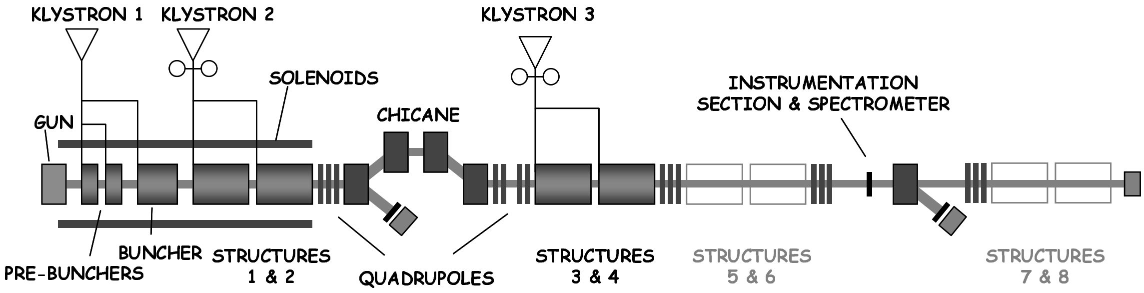

Figure 2: Schematic layout of the CTF3 injector and the first linac modules during 2003 commissioning.

THE CTF3 INJECTOR AND LINAC

The drive beam injector was built by a collaboration between SLAC (gun triode and beam dynamics design), LAL-Orsay (gun electronics, high-voltage equipment and pre-bunchers) and CERN. The 1.5 μs long beam pulse is generated by a 140 kV thermionic gun. The present 3 GHz bunching system is composed of two single-cell standing-wave pre-bunchers and a graded-β travelling-wave buncher. It provides bunches spaced by 10 cm, at an energy of 5 MeV, and is followed by two travelling wave structures, which bring the beam energy up to about 20 MeV. Solenoidal focusing is used all along the injector. A magnetic chicane with collimators is used to eliminate low energy beam tails and to perform bunch compression.

In its final configuration, the CTF3 linac will be composed of 11 modules. Each module is 4.5 m long and contains a quadrupole triplet. Eight modules will include two travelling-wave structures each, while three modules will be equipped with beam instrumentation. The 3 GHz structures [5] work in the 2π/3 mode, have a total length of 1.22 m and operate at a loaded gradient (nominal current) of 6.5 MV/m. In order to suppress the transverse Higher Order Modes (HOMs) the structures (called SICA, for Slotted Iris Constant Aperture) use four radial slots in the iris to couple out the HOMs to SiC loads. The mode selection is obtained through the field distribution, so that all dipole modes are damped. The Q-value of the first dipole is reduced below 20. A further reduction of the long-range wake-fields is achieved by detuning the HOM frequencies along the structure, using nose cones of variable geometry combined with different cell radii.

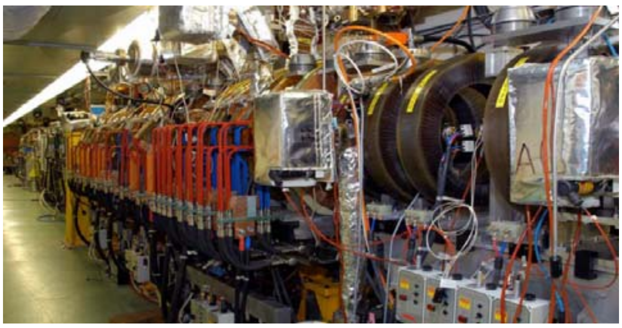

Figure 3: View of the CTF3 injector from the gun.

Simulations have shown that the beam emittance is conserved during acceleration despite the high beam current and the long beam pulse. The RF power is supplied by klystrons with power ranging from 35 MW to 45 MW and compressed by a factor 2 to provide 1.5 μs pulses over 30 MW at each structure input. The pulse compression system uses a programmed phase ramp to get a rectangular pulse.

COMMISSIONING RESULTS

In 2003 the injector and the first three linac modules were installed (see Figs. 2 and 3). Beam commissioning started in June 2003. The design beam current and pulse length were rapidly reached, successfully demonstrating the operation under nominal working conditions of the structures with their novel damping scheme.

Full Beam Loading Operation

The main result obtained was the first proof of stable operation under full beam loading. The beam was remarkably stable and no sign of beam break-up was observed at high current. The energy spread during the initial beam transient (about 100 ns) could be easily reduced to a few percent by partial RF filling of the structures at beam injection. The observation of the RF signals at the structures' output coupler (see Fig. 4) was particularly useful. It allowed for instance to set up easily the beam-to-RF phase by maximizing the beam loading and to determine the phase error between structures.

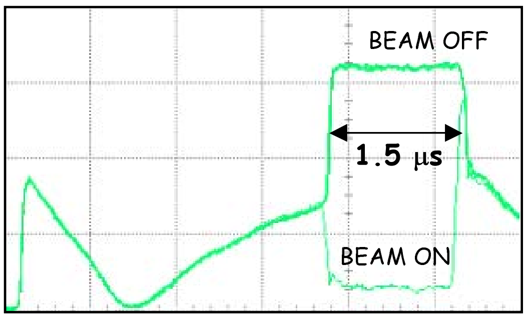

Figure 4: Scope trace showing the RF pulse at the output coupler of a structure. When the beam is on, it extracts more than 90 % of the energy contained in the useful part of the RF pulse (1.5 μs). Virtually no power goes to the load.

The RF signals were also used to assess the RF-to-beam efficiency. This was done by measuring the RF power level at the structure input and output for a given beam current. The values obtained were then compared to both the measured beam energy gain and the calculations, with a good agreement. In the example of Fig. 4 the beam current was 4 A. The power at the structure input was 35 MW, and the power to the load was 0.4 MW with beam. The expected value of the Ohmic losses is 1.6 MW. The 33 MW of "missing power" agrees well with the beam energy gain in momentum (~ 8.2 MeV per structure). The RF-to-beam efficiency thus evaluated is 94 %.

Other commissioning results

The gun provided a maximum current of 9 A at 140 keV, its design value. Above this value, a pulse-to-pulse current jitter starts to appear. The pulse length can be varied between 200 ns and 1.5 μs.

The operation of the first pre-buncher (copper, high-Q) was difficult due to multipactoring and to input RF power reflection, caused by beam-induced detuning. Therefore, high-current operation was carried out powering only the second pre-buncher (stainless steel, low external Q), which was not plagued by these problems. With only one pre-buncher the performances were somewhat reduced, but nevertheless the bunching system showed a satisfying capture efficiency of about 75 %. The nominal current of 3.5 A was obtained after the momentum cleaning chicane for a gun current of about 5 A. The beam energy, measured in the end-of-line spectrometer, was 35 MeV. Indeed, the nominal beam current could be largely exceeded, and the higher current transported to the final dump was 5 A (with 7.5 A provided from the gun).

A variety of beam measurements were performed. Beam emittance was measured with the quadrupole scan technique using an Optical Transition Radiation (OTR) aluminium screen and a CCD camera. The measured rms normalized emittance was close to the nominal value of 100 π mm mrad in both planes, although some of the scans taken in the vertical plane were not consistent. The likely cause, a limited resolution of the beam size measurement, has been corrected and we plan to perform further measurements this year. The design value of the rms bunch length is 5 ps, a fundamental parameter for the CTF3 linac. Bunch length was determined with an OTR screen and a streak camera, as well as by measuring the beam energy spread as a function of the RF phase. The measured value was about 4 ps for 3.5 A beam current, without magnetic compression. A preliminary test of bunch compression was also performed. Streak camera measurements in that case gave an rms bunch length around 2 ps, at the limit of the streak camera resolution.

Other activities during commissioning included development studies of a beam loss monitor system [6] and of beam halo measurements [7].

CTF3 Commissioning in 2004

During the winter shut-down more modules were installed, bringing the total number of accelerating structures to 10. A dog-leg transport line was installed after the instrumentation module, together with a new 30 GHz power test stand, where the drive beam can be used to generate 30 GHz RF power in a special power Extraction and Transfer Structure (PETS). The commissioning of the newly installed hardware is presently under way, and the first 30 GHz RF pulses have already been produced, with moderate beam current. At present only a short PETS is installed, and preliminary measurements indicate a power above 100 kW, in accord to the expected value.

CONCLUSIONS

The commissioning of the CTF3 injector and of the first three linac modules was successfully carried out in 2003.

The main beam parameters were obtained and in some cases exceeded, and beam measurements showed a good agreement with expectations. The highlight of the commissioning period was the first demonstration of the full beam loading operation, a key issue for the CLIC design, with measured RF-to-beam transfer efficiencies higher than 90 %. During the winter shut-down more linac modules were installed, as well as a new 30 GHz power test line, which is presently being commissioned. It has already produced 30 GHz RF pulses beyond the nominal CLIC pulse length, although at low power.

The next milestones for CTF3 will be the completion of the linac and of the following bunch stretcher chicane in summer 2004, and its commissioning in autumn.

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