EXPERIMENTAL STUDIES ON DRIVE BEAM GENERATION IN CTF3

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Abstract

The objective of the CLIC Test Facility CTF3, built at CERN by an international collaboration, is to demonstrate the main feasibility issues of the CLIC two-beam technology by 2010. CTF3 consists of a 150 MeV electron linac followed by a 42 m long delay loop, an 84 m combiner ring and a two-beam test area. One key-issue studied in CTF3 is the efficient generation of a very high current drive beam, used in CLIC as the power source for the acceleration of the main beam to multi-TeV energies. The beam current is first doubled in the delay loop and then multiplied again by a factor four in the combiner ring by interleaving bunches using transverse deflecting RF cavities. The combiner ring and the connecting transfer line have been installed and put into operation in 2007. In this paper we give the status of the commissioning, illustrate the beam optics measurements, discuss the main issues and present the results of the combination tests.

THE CTF3 COMPLEX

It is generally accepted that the CLIC technology [1] is the only possible path to multi-TeV colliders. However, several critical issues still need to be addressed. The experimental program of the present CLIC Test Facility, CTF3 [2], tackles most of them and in particular the generation and use of the high-current drive beam [3]. CTF3 is presently being built and commissioned at CERN by an international collaboration which at present includes 24 institutes from 14 countries [4].

The facility is placed in the buildings of the former LEP Pre-Injector, LPI (see Fig. 1), the hardware of which is partly re-used. It includes a 70 m long drive-beam linac followed by two rings, where the beam current is multiplied by a factor eight: a 42 m delay loop and an 84 m combiner ring. The drive beam is then transported to the CLic EXperimental area (CLEX) to produce 12 GHz RF power for structure tests. In the same area, the CALIFES linac will provide a probe beam for a Two-Beam Test Stand (TBTS) and a decelerator (Test Beam Line – TBL) will be used for drive beam stability studies.

The drive beam injector includes a thermionic gun, three 1.5 GHz sub-harmonic bunchers (SHB), a 3 GHz bunching system and two 3 GHz accelerating structures. Solenoidal focusing is used all along. A three-bends chicane with collimators is then used to eliminate off-energy particles and to perform bunch compression. A beam current of 3 to 4 A with a momentum of about 25 MeV/c is typically achieved at the end of the injector.

The linac is composed of 11 modules, 8 of which are equipped with two travelling-wave structures each. A module is 4.5 m long and contains a quadrupole triplet.

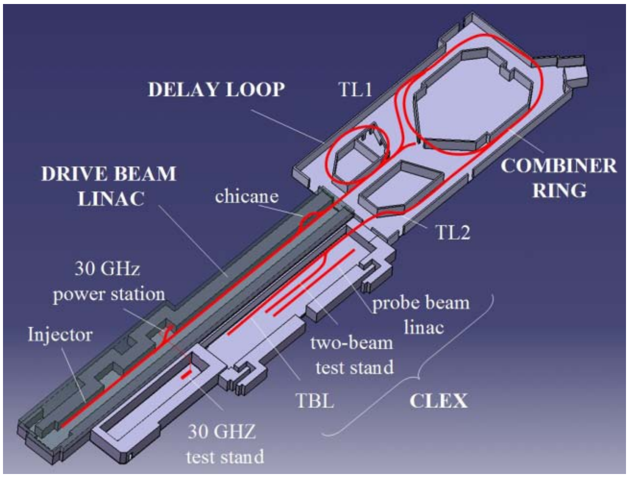

Figure 1: Schematic layout of the CTF3 complex.

The structures have a length of 1.22 m and operate at a full-loaded gradient of 6.5 MV/m. They use radial damping slots plus cell-to-cell detuning in order to control transverse wake-fields. Each module is powered by a klystron with peak power in the 35 MW to 45 MW range, doubled by RF compression to provide more then 30 MW at each structure input. The pulse compression system uses a programmed phase ramp to obtain a 1.5 µs flat top. A beam line branches off halfway along the linac. The beam can be sent there to be decelerated in a Power Extraction and Transfer Structure (PETS) and produce 30 GHz power, brought via a low-loss waveguide to a test stand in the former CTF II hall.

A four-bend magnetic chicane with variable momentum compaction factor is located at the end of the linac and is used to optimize the bunch length. Simulations have in fact shown that bunches with nominal bunch charge (2.5 nC) and less than 1 mm rms length would suffer from coherent synchrotron radiation effects in the delay loop and in the combiner ring. The delay loop has a two-fold symmetry, with double injection/extraction septa and 10 bending magnets. It includes an RF deflector used for injection/extraction and a wiggler for path length tuning. The design optics is achromatic and isochronous. A four dipole transfer line (TL1) with tuneable momentum compaction connects the delay loop to the combiner ring. The combiner ring has four achromatic and isochronous arcs, with three dipoles each. Injection and extraction regions are located in the long straight sections. For injection, two horizontal RF deflectors separated by a π betatron phase advance and located at each side of the injection septa are used. On the opposite side, a fast kicker is used for extraction. The ring has also a path-length tuning wiggler in one of the two short straights.

NEW INSTALLATIONS

A transfer line (TL2) with variable momentum compaction [55] will join the ring to the beam lines in CLEX, a hall of 42 m length and 8 m width, partly covered by a gallery for klystrons, power supplies and other equipment. Most of TL2 is already in place, and the line will be completed before the end of July 2008, during a dedicated shut down. The installation of the CALIFES probe beam injector [5] and of the TBTS [6] is also close to completion, and the last components will be installed in the same period. CALIFES will produce a low current electron beam in a photo injector and accelerate it to 170 MeV in three structures re-used from the former LPI. Both single-bunch and bunch-train operation will be possible. The probe beam will then be further accelerated by 12 GHz structures in the TBTS, which will also allow high-power testing of a PETS prototype with a drive beam of up to 30 A of beam current. The PETS has the same cross section as in CLIC, being only longer in order to produce the same peak power. It has a power recirculation circuit which can be used to enhance power extraction and will eventually be equipped with an on/off mechanism. Different structures could be tested in the TBTS, which is well instrumented to analyse their behaviour as well as the effect of RF breakdowns on the probe beam. In addition, in the TBL [7] final configuration the drive beam will be decelerated to about half its initial energy by up to 16 PETS. The aim is to demonstrate beam stability under significant deceleration, which will produce a momentum difference of up to a factor two between the first and the last bunches. The TBL is composed of modules, each one including a PETS, a beam position monitor (BPM) and a quadrupole on a movable support, in order to test beam-based alignment procedures. A total of about 2 GW of 12 GHz RF power can be extracted from the beam. Only one module of the TBL will be installed this year. The whole decelerator should come online in 2009.

COMMISSIONING STATUS

In 2003-2004 the injector, the linac, the mid-linac power station and the end-of-linac magnetic chicane were installed and commissioned. Full beam-loading operation was established [8] and the beam resulted remarkably stable, with no sign of beam break-up. An rf-to-beam efficiency of 94 % has been experimentally verified later on [9]. The first part of the linac is routinely used since 2005 as a source of 30 GHz RF power. Up to 100 MW can be produced in the PETS, and transported to the test stand with ~ 70 % efficiency. The delay loop was installed during 2005 and commissioned in 2006. Five 140 ns long bunch-trains were injected into the delay loop and combined with the following train, thus doubling the beam current [10]. In 2006 a short period was dedicated to the commissioning of the newly installed TL1. Short pulses of 200 ns were used. The beam was rapidly transported to the end of the line and a current of 3 A could be injected in the ring first straight section.

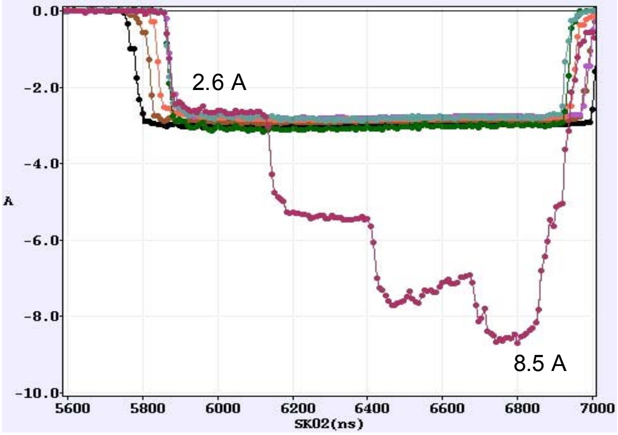

Figure 2: Beam current multiplication in the combiner ring. The traces show the beam current measured in several BPMs in the linac and TL1, and in one ring BPM. The incoming pulse has four times the ring length (4 × 280 ns). Losses from instability in the last two turns don't allow to reach a full factor four in current gain.

The combiner ring installation was completed at the beginning of 2007. Commissioning of the transfer line TL1 and of the combiner ring to the nominal beam performance continued in 2007, with several interruptions for repairs and installation work [11], and is presently under way. Several problems in the hardware and in the optics model were identified, mainly through beam measurements, and eventually fixed, including wrong BPM calibration and connections, quadrupole cabling errors, switched polarities and wrong current calibrations. The alignment of magnets and vacuum chamber elements was also re-checked and corrected when necessary. During 2007 we could finally obtain a beam circulating for several turns in the ring, albeit with non-negligible losses. A fast beam instability in the vertical plane was indeed discovered [12], which gives rise to growing vertical beam oscillations and eventually to beam loss.

The instability is believed to be caused by the vertical deflecting mode in the RF deflectors, excited by the beam. This mode is shifted in frequency by 48 MHz with respect to the horizontal deflecting mode by polarising rods in the deflector cells, but it is not damped. New RF deflectors are being built, to be installed in October 2008 [13]. At the end of the 2007 run, a recombination test over four turns was performed anyway, bypassing the delay loop (see Fig. 2). In 2008 the ring commissioning restarted. Waiting for the installation of the new deflectors in October, the aim is to clarify the last minor inconsistencies between the model and the machine and to explore the possibility to control the vertical instability by a proper choice of the vertical tune in the ring and of the β-function in the RF deflectors [12].

MEASUREMENTS

Several beam optics measurements were performed in CTF3 during the 2007 and 2008 runs. Among others:

1. Standard quadrupole scans, used to check the optics and perform re-matching of the different beam lines.

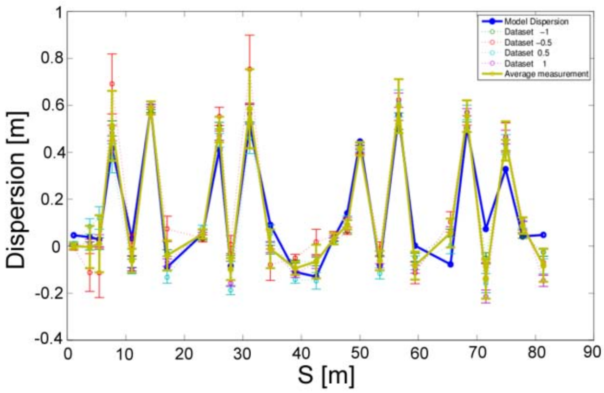

Figure 3: Results of dispersion measurements in the combiner ring (yellow line) compared with predictions from the MAD model (blue line).

2. Determination of transverse response matrix elements by orbit measurements with kick excitation. The data obtained were paramount in order to identify and correct errors in the quadrupole families.

3. Dispersion, typically measured by varying the strength of all magnetic elements over a 1% range and taking the orbit difference. Such technique is simpler then a beam energy change and has the additional advantage that dispersion can be measured locally, not being sensitive to incoming residual dispersion. A good agreement was found in all machine areas. See an example in Fig. 3.

4. Tune measurements, by FFT of horizontal and vertical signals of the ring BPMs. The measurements have shown, like kick-orbit studies, a disagreement with the MAD model. After the last corrections to the model and the calibration adjustments, a new measurement campaign is still required for verification.

5. Determination of the closed orbit. A first estimate is done by averaging the first few turns. The injection is then optimized to minimize the turn-to-turn difference. An automatic closed orbit correction program is at present under test.

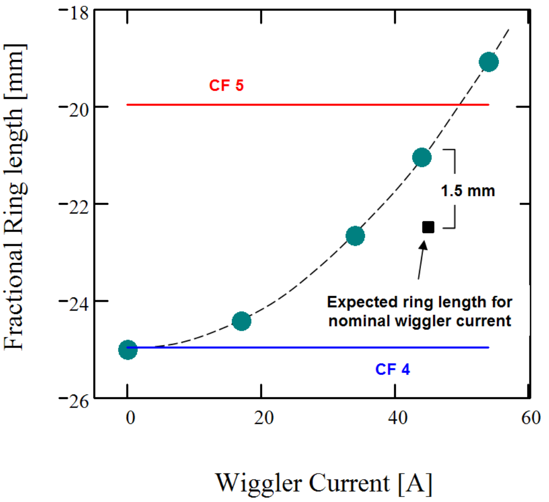

Figure 4: Ring length as a function of the tuning wiggler current. The actual length is an integer number of 3 GHz wavelengths, plus the fractional part shown here. The circles are measured values and the dashed line the expected variation. The black square is the nominal value and the horizontal lines mark the operational range.

6. Measurement of the ring length, fundamental since the recombination process relies on a precise control of the revolution time, to the 10^{-5} level. The measurement was done using a 3 GHz RF phase monitor. An FFT of the signal gives the ring length modulo the RF wavelength (see Fig.4). The ring was found to be 1.5 mm longer than the nominal. A good closed orbit correction (not applied then) may in principle reduce the discrepancy, which is however within the limits of the needed operational range (corresponding to 4-turn to 5-turn recombination). The path length variation as a function of the tuning wiggler current behaved exactly as expected.

CONCLUSIONS

The CTF3 project is the main tool to demonstrate the feasibility of the CLIC scheme, in particular the generation of the high-current drive beam. A number of issues have already been addressed, such as full beam loading operation and the bunch phase coding and interleaving scheme. Commissioning of the combiner ring is in progress and a full combination test is expected after installation of the new RF deflectors, needed to damp the fast vertical instability which is the present limiting factor.

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