Performance Chapter

- Overview of system tests performed so far, and aimed at ensuring the CLIC performance (includes also availability studies)
  - Basically all material exists, and must just be assembled in the proper form
  - Less need for absolute coherence in parameters, etc…
  - Not so much coupled with the rest
  - All this allowed for a relatively advanced state
  - We are preparing in parallel a CTF3 Report, much more extensive than the corresponding section in the Performance Chapter.
    (To be considered for other system tests?)

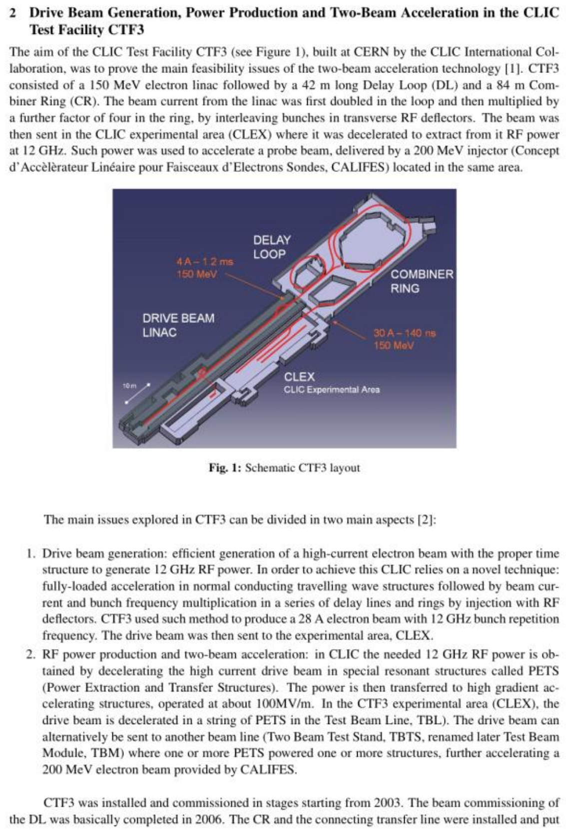
Performance Chapter - Status

Chapter	Section	Pages (plan)	Pages (received)	Comments	Responsible	Status
	Introduction	2	0	Overview, include reference to SLC	Daniel (Roberto, Phil)	😐 Wait for first draft of the rest
	Drive Beam	3	6	CTF3	Roberto	⍰
	BDS beam dynamics	3	2	ATF2, FFTB	Rogelio	⍰
	Main linac beam dynamics	3	4	FACET+ELETTRA	Andrea	⍰
	RF systems	3	3	Swiss FEL, X-boxes, Compact light, …	Walter (Nuria, Gerry)	⍰ 2nd version received
	DR	3	0	Light sources whatever	Yannis	😐 It should arrive today
	Availability studies	2	0	Moved to Daniel’s chapters	Odei	⍰ received
	Other effects	2	4	magnetic fields (what else?)	Edu, Daniel	⍰ Magn. Fields OK
SUM		**21**	**19**			

All received contributions in Latex (or converted), assembled in an Overleaf Project.

Already pretty good. Probably need some more coherence in style and depth. Introduction to be added.

Ready to be handled over to the editors.



2 Drive Beam Generation, Power Production and Two-Beam Acceleration in the CLIC Test Facility CTF3

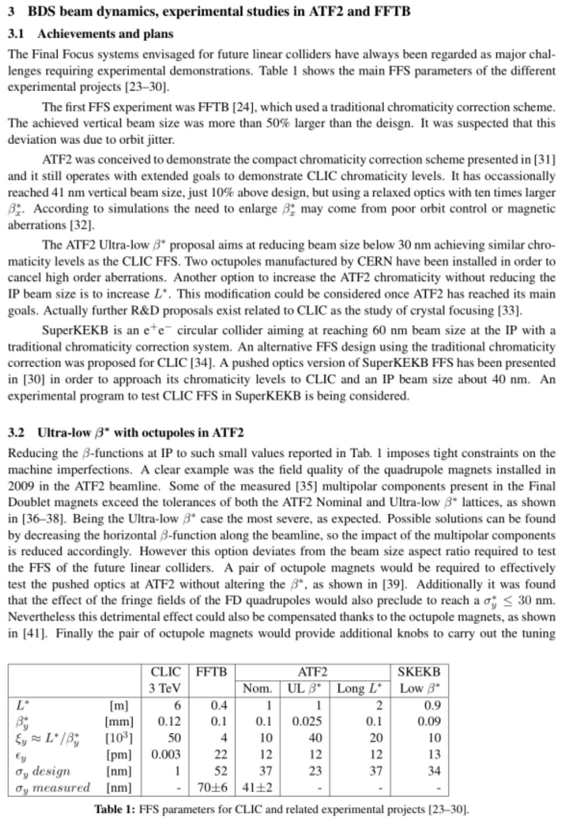
The aim of the CLIC Test Facility CTF3 (see Figure 1), built at CERN by the CLIC International Collaboration, was to prove the main feasibility issues of the two-beam acceleration technology [1]. CTF3 consisted of a 150 MeV electron linac followed by a 42 m long Delay Loop (DL) and a 84 m Combiner Ring (CR). The beam current from the linac was first doubled in the loop and then multiplied by a further factor of four in the ring, by interleaving bunches in transverse RF deflectors. The beam was then sent in the CLIC experimental area (CLEX) where it was decelerated to extract from it RF power at 12 GHz. Such power was used to accelerate a probe beam, delivered by a 200 MeV injector (Concept d'Accèlèrateur Linéaire pour Faisceaux d'Electrons Sondes, CALIFES) located in the same area.

Fig. 1: Schematic CTF3 layout

The main issues explored in CTF3 can be divided in two main aspects [2]:

1. Drive beam generation: efficient generation of a high-current electron beam with the proper time structure to generate 12 GHz RF power. In order to achieve this CLIC relies on a novel technique: fully-loaded acceleration in normal conducting travelling wave structures followed by beam current and bunch frequency multiplication in a series of delay lines and rings by injection with RF deflectors. CTF3 used such method to produce a 28 A electron beam with 12 GHz bunch repetition frequency. The drive beam was then sent to the experimental area, CLEX.
2. RF power production and two-beam acceleration: in CLIC the needed 12 GHz RF power is obtained by decelerating the high current drive beam in special resonant structures called PETS (Power Extraction and Transfer Structures). The power is then transferred to high gradient accelerating structures, operated at about 100MV/m. In the CTF3 experimental area (CLEX), the drive beam is decelerated in a string of PETS in the Test Beam Line, TBL). The drive beam can alternatively be sent to another beam line (Two Beam Test Stand, TBTS, renamed later Test Beam Module, TBM) where one or more PETS powered one or more structures, further accelerating a 200 MeV electron beam provided by CALIFES.

CTF3 was installed and commissioned in stages starting from 2003. The beam commissioning of the DL was basically completed in 2006. The CR and the connecting transfer line were installed and put



3 BDS beam dynamics, experimental studies in ATF2 and FFTB

3.1 Achievements and plans

The Final Focus systems envisaged for future linear colliders have always been regarded as major challenges requiring experimental demonstrations. Table 1 shows the main FFS parameters of the different experimental projects [23–30].

The first FFS experiment was FFTB [24], which used a traditional chromaticity correction scheme. The achieved vertical beam size was more than 50% larger than the deisgn. It was suspected that this deviation was due to orbit jitter.

ATF2 was conceived to demonstrate the compact chromaticity correction scheme presented in [31] and it still operates with extended goals to demonstrate CLIC chromaticity levels. It has occassionally reached 41 nm vertical beam size, just 10% above design, but using a relaxed optics with ten times larger β_x^*. According to simulations the need to enlarge β_x^* may come from poor orbit control or magnetic aberrations [32].

The ATF2 Ultra-low β^* proposal aims at reducing beam size below 30 nm achieving similar chromaticity levels as the CLIC FFS. Two octupoles manufactured by CERN have been installed in order to cancel high order aberrations. Another option to increase the ATF2 chromaticity without reducing the IP beam size is to increase L^*. This modification could be considered once ATF2 has reached its main goals. Actually further R&D proposals exist related to CLIC as the study of crystal focusing [33].

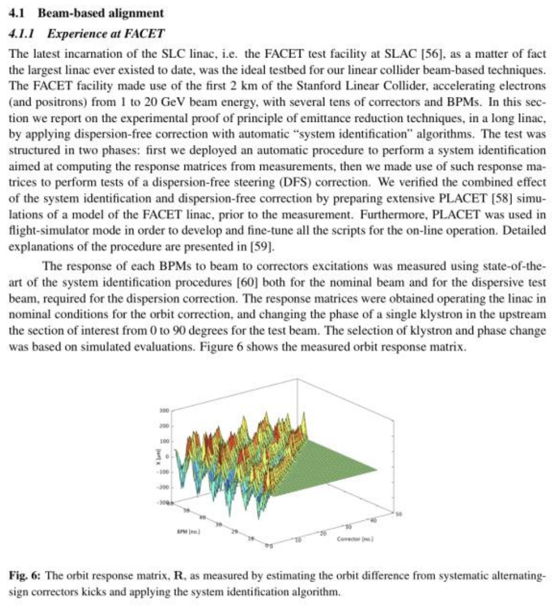
SuperKEKB is an e^+e^- circular collider aiming at reaching 60 nm beam size at the IP with a traditional chromaticity correction system. An alternative FFS design using the traditional chromaticity correction was proposed for CLIC [34]. A pushed optics version of SuperKEKB FFS has been presented in [30] in order to approach its chromaticity levels to CLIC and an IP beam size about 40 nm. An experimental program to test CLIC FFS in SuperKEKB is being considered.

3.2 Ultra-low β^* with octupoles in ATF2

Reducing the β-functions at IP to such small values reported in Tab. 1 imposes tight constraints on the machine imperfections. A clear example was the field quality of the quadrupole magnets installed in 2009 in the ATF2 beamline. Some of the measured [35] multipolar components present in the Final Doublet magnets exceed the tolerances of both the ATF2 Nominal and Ultra-low β^* lattices, as shown in [36–38]. Being the Ultra-low β^* case the most severe, as expected. Possible solutions can be found by decreasing the horizontal β-function along the beamline, so the impact of the multipolar components is reduced accordingly. However this option deviates from the beam size aspect ratio required to test the FFS of the future linear colliders. A pair of octupole magnets would be required to effectively test the pushed optics at ATF2 without altering the β^*, as shown in [39]. Additionally it was found that the effect of the fringe fields of the FD quadrupoles would also preclude to reach a $\sigma_y^* \leq 30$ nm. Nevertheless this detrimental effect could also be compensated thanks to the octupole magnets, as shown in [41]. Finally the pair of octupole magnets would provide additional knobs to carry out the tuning

		CLIC	FFTB	ATF2			SKEKB
		3 TeV		Nom.	UL β^*	Long L^*	Low β^*
L^*	[m]	6	0.4	1	1	2	0.9
β_y^*	[mm]	0.12	0.1	0.1	0.025	0.1	0.09
$\xi_y \approx L^*/\beta_y^*$	[10^3]	50	4	10	40	20	10
ϵ_y	[pm]	0.003	22	12	12	12	13
σ_y *design*	[nm]	1	52	37	23	37	34
σ_y *measured*	[nm]	-	70±6	41±2	-	-	-

Table 1: FFS parameters for CLIC and related experimental projects [23–30].



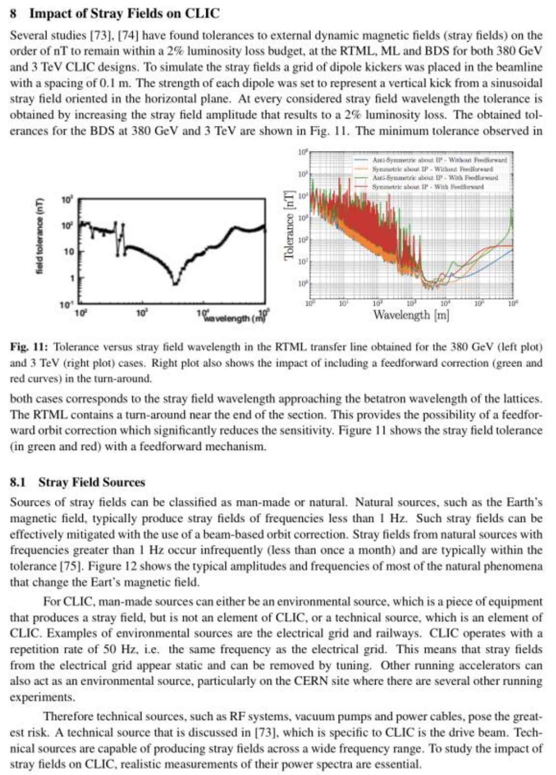
4.1 Beam-based alignment

4.1.1 Experience at FACET

The latest incarnation of the SLC linac, i.e. the FACET test facility at SLAC [56], as a matter of fact the largest linac ever existed to date, was the ideal testbed for our linear collider beam-based techniques. The FACET facility made use of the first 2 km of the Stanford Linear Collider, accelerating electrons (and positrons) from 1 to 20 GeV beam energy, with several tens of correctors and BPMs. In this section we report on the experimental proof of principle of emittance reduction techniques, in a long linac, by applying dispersion-free correction with automatic "system identification" algorithms. The test was structured in two phases: first we deployed an automatic procedure to perform a system identification aimed at computing the response matrices from measurements, then we made use of such response matrices to perform tests of a dispersion-free steering (DFS) correction. We verified the combined effect of the system identification and dispersion-free correction by preparing extensive PLACET [58] simulations of a model of the FACET linac, prior to the measurement. Furthermore, PLACET was used in flight-simulator mode in order to develop and fine-tune all the scripts for the on-line operation. Detailed explanations of the procedure are presented in [59].

The response of each BPMs to beam to correctors excitations was measured using state-of-the-art of the system identification procedures [60] both for the nominal beam and for the dispersive test beam, required for the dispersion correction. The response matrices were obtained operating the linac in nominal conditions for the orbit correction, and changing the phase of a single klystron in the upstream the section of interest from 0 to 90 degrees for the test beam. The selection of klystron and phase change was based on simulated evaluations. Figure 6 shows the measured orbit response matrix.

Fig. 6: The orbit response matrix, **R**, as measured by estimating the orbit difference from systematic alternating-sign correctors kicks and applying the system identification algorithm.



8 Impact of Stray Fields on CLIC

Several studies [73], [74] have found tolerances to external dynamic magnetic fields (stray fields) on the order of nT to remain within a 2% luminosity loss budget, at the RTML, ML and BDS for both 380 GeV and 3 TeV CLIC designs. To simulate the stray fields a grid of dipole kickers was placed in the beamline with a spacing of 0.1 m. The strength of each dipole was set to represent a vertical kick from a sinusoidal stray field oriented in the horizontal plane. At every considered stray field wavelength the tolerance is obtained by increasing the stray field amplitude that results to a 2% luminosity loss. The obtained tolerances for the BDS at 380 GeV and 3 TeV are shown in Fig. 11. The minimum tolerance observed in both cases corresponds to the stray field wavelength approaching the betatron wavelength of the lattices. The RTML contains a turn-around near the end of the section. This provides the possibility of a feedforward orbit correction which significantly reduces the sensitivity. Figure 11 shows the stray field tolerance (in green and red) with a feedforward mechanism.

Fig. 11: Tolerance versus stray field wavelength in the RTML transfer line obtained for the 380 GeV (left plot) and 3 TeV (right plot) cases. Right plot also shows the impact of including a feedforward correction (green and red curves) in the turn-around.

8.1 Stray Field Sources

Sources of stray fields can be classified as man-made or natural. Natural sources, such as the Earth's magnetic field, typically produce stray fields of frequencies less than 1 Hz. Such stray fields can be effectively mitigated with the use of a beam-based orbit correction. Stray fields from natural sources with frequencies greater than 1 Hz occur infrequently (less than once a month) and are typically within the tolerance [75]. Figure 12 shows the typical amplitudes and frequencies of most of the natural phenomena that change the Eart's magnetic field.

For CLIC, man-made sources can either be an environmental source, which is a piece of equipment that produces a stray field, but is not an element of CLIC, or a technical source, which is an element of CLIC. Examples of environmental sources are the electrical grid and railways. CLIC operates with a repetition rate of 50 Hz, i.e. the same frequency as the electrical grid. This means that stray fields from the electrical grid appear static and can be removed by tuning. Other running accelerators can also act as an environmental source, particularly on the CERN site where there are several other running experiments.

Therefore technical sources, such as RF systems, vacuum pumps and power cables, pose the greatest risk. A technical source that is discussed in [73], which is specific to CLIC is the drive beam. Technical sources are capable of producing stray fields across a wide frequency range. To study the impact of stray fields on CLIC, realistic measurements of their power spectra are essential.

5 Performance of high-gradient rf systems

The performance of the CLIC main linac rf system has been studied from a comprehensive range of perspectives and the results show that all major performance criteria and specifications can be achieved. The different performance categories are structured in a list below in order to give an overview. Highlights of developments which have occurred since the CDR are addressed individually in more detail below. In the last part of this section relevant performances of other linacs are described. Performance criteria for the high-gradient rf system:

- Accelerating gradient
  - 3 TeV structure – 100 MV/m loaded
  - 380 GeV structure – 72 MV/m loaded
  - The effect of beam loading
  - Conditioning, variability and long term operation
- Power production – two beam
  - PETS power capability
  - Power modulation
- Power production – klystron-based
  - Modulator
  - Klystron
  - Pulse compressor
  - Waveguide components
  - Control and operation
  - Integrated system operation

The most challenging performance parameter is the accelerating gradient. For example the required 3 TeV gradient is a factor three higher than the one in state-of-the-art operational linacs. But already by the time of the CDR, accelerating structures were operated at full pulse length and CLIC nominal breakdown rate in excess of 100 MV/m (unloaded) showing the fundamental feasibility of the 3 TeV design.

In the intervening period, testing has continued in order to continue to address and improve accelerating gradient related performance issues including final performance, conditioning time and strategy, optimized recovery from breakdown and operational strategy, variation among structures and long term behavior [performance references]. In addition the testing has also had the objective to determine and improve the performance of the complete high-power rf system including modulators, klystrons, pulse compressors, waveguide network, low-level rf etc. In order to address this broad range of issues the rf test stand infrastructure has been significantly increased. There are now three X-band test stands with a total of six testing slots currently under operation at CERN [test stand references]. Testing in Nextef at KEK continues as well.

The accelerating structures which have been operated during the past five years are all test versions of the CLIC-G 3 TeV structure, but which incorporate varying degrees of complexity; without damping waveguides, with damping waveguides, with mode-launcher then compact coupler and finally including SiC absorbers and associated manifolds. The strategy to implement key features one at a time was to determine the effects on performance of each individually. The testing program has continued with the CLIC-G based structures in order to complete this study and to be able to make direct comparisons to existing benchmark data. A summary plot of the performances of CLIC-G (3 TeV) type structures is shown in Figure 10.