CHALMERS
UNIVERSITY OF TECHNOLOGY

Drive beam stability studies and stabilization algorithms in CLIC Test Facility 3

Citation for the original published paper (version of record):
Persson, T., Skowroński, P., Corsini, R. (2014). Drive beam stability studies and stabilization algorithms in CLIC Test Facility 3. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 735: 152-156.
http://dx.doi.org/10.1016/j.nima.2013.09.038

Nuclear Instruments and Methods in Physics Research A 735 (2014) 152–156

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Drive beam stability studies and stabilization algorithms in CLIC Test Facility 3

T. Persson [a,b,*], P. Skowronski [a], R. Corsini [a]

[a] CERN, CH-1211 Geneva 23, Switzerland
[b] Chalmers University of Technology, 412 96 Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form
10 September 2013
Accepted 13 September 2013
Available online 20 September 2013

Keywords:
CLIC Test Facility
Beam stability
Feedback
RF-pulse compression

ABSTRACT

In this paper the study of the mechanisms responsible for the time varying beam current losses in CTF3 (CLIC Test Facility 3), together with the feedbacks implemented to mitigate them, is presented. The study shows that the losses were linked mainly to the energy variation induced by the RF (Radio frequency) amplitude fluctuations. The RF-amplitude instability sources were identified. A feedback developed to mitigate this instability, acting on the RF-compression system by controlling the phase program of the klystron, is described in detail. The result is a significant improvement of the overall stability in the machine. The energy variation is reduced further with the use of an energy feedback operating on the RF-amplitude of the last klystron in the CTF3 linac. This feedback loop closes on the energy measured from a dispersive pickup after the linac. With the energy stabilized a beam current stability close to the CLIC (Compact Linear Collider) specification for a factor 4 combined beam was achieved.

1. Introduction

CLIC (Compact Linear Collider) is a possible next generation e^+e^- collider. The design relies upon a two-beam acceleration scheme, where one of the beams, referred to as the Drive Beam, is decelerated to create high fields used to accelerate the other beam, referred to as the Main Beam. The two-beam acceleration scheme puts tight constraint on the beam current stability of the Drive Beam. The tight tolerance derives from the fact that any current variation of the Drive Beam translates into a change in accelerating gradient which in turn gives a variation of the energy of the Main Beam. This leads to a decrease in luminosity mainly due to two mechanisms: First, the limited energy bandwidth of the Beam Delivery System and second, an increase of the emittance in the main linac. This has lead to the stability requirement of the Drive Beam: $\sigma_I/I = 7.5\times10^{-4}$ [1]. In simulations this corresponds to a decrease in luminosity of 1% compared to the ideal machine without any beam current variation. The decrease is observed to be quadratic with respect to the current variation [2].

A beam current stability of $\sigma_I/I < 4\times10^{-4}$, well below the CLIC specification, has been demonstrated in the CTF3 (CLIC Test Facility 3) linac [3]. This has been possible by improving the thermionic gun high-voltage and pulser system, including the use of a feedback [4,1]. However, as the beam is transported from the linac to the combiner ring the beam current stability degrades due to losses related mainly due to the energy variations. Controlling these losses is essential to reach the CLIC requirements. The losses and their causes are also clearly disturbing for the experiments in CTF3 [5]. In Section 2 the method used to establish the causes of the observed drifts is described.

1.1. CLIC test facility 3

CTF3 is a test facility at CERN built to experimentally demonstrate some of the key concepts for CLIC [6]. A major concern in its mission to demonstrate the concepts has been the stability and reproducibility of the beam.

In CTF3 the beam is generated in a similar manner as foreseen for CLIC but with lower energy and shorter pulse length. The layout of the CTF3 complex is shown in Fig. 1 and described in detail in Ref. [3]. The acceleration of the beam is performed in the linac. All the klystrons, except the first, send RF (Radio Frequency) power to a pulse compressor. The high-Q resonant cavities are used to convert 5.5 μs pulses into 1.3 μs ones with double peak power [7]. The energy storage cavities used for the pulse compression must be very precisely tuned in frequency. Fig. 2 shows a conceptual picture of the phase program and how it relates to the output power after compression. The phase program has a linear ramp during the build up of the power in the cavity, between A and B in Fig. 2. This slope is optimized to reduce the static phase variation of the pulse during the flattop of the power

* Corresponding author at: CERN, CH-1211 Geneva 23, Switzerland. Tel.: +41 764879645.
E-mail address: tobias.persson@cern.ch (T. Persson).

http://dx.doi.org/10.1016/j.nima.2013.09.038
0168-9002/

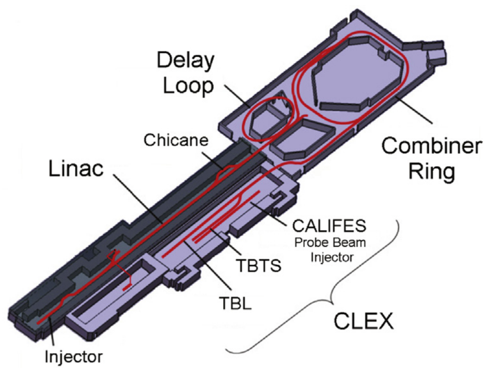

Fig. 1. A schematic overview of the CTF3 complex.

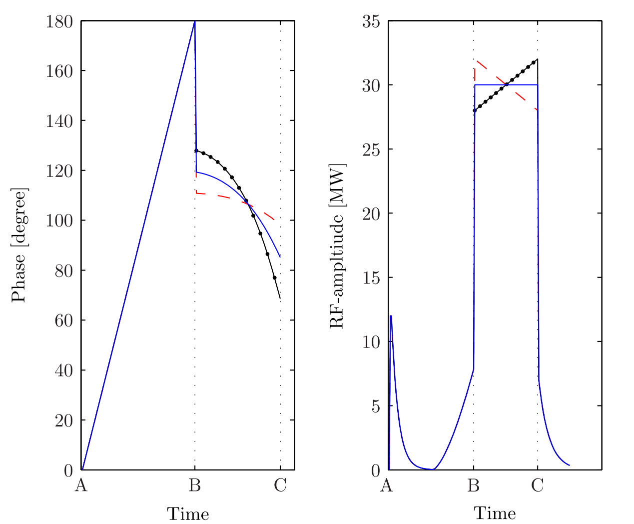

Fig. 2. The left plot shows the conceptual idea of the phase program. In the right the corresponding output power after the pulse compressor is shown. The different markers show conceptually how the phase program affects the output power. Note that the *x*-axis is not to scale. The distance in time between A and B is $\sim 4\ \mu s$, between B and C $1.3\ \mu s$.

and to maximize the compression efficiency. A phase jump is then introduced to release the power built up to the accelerating structure, at point B. Next part of the phase function, between B and C, is used to create the flat output power of the RF-amplitude [8,9]. After the pulse compressor the pulse is split and sent to two accelerating structures. It should be stressed that the challenges faced with the RF-pulse compression are specific to CTF3 and will not be present at CLIC, where it will not be used.

The beam operation mode that will be described in this paper is a 3 GHz beam, accelerated in the linac to ~ 125 MeV, bypassing the delay loop, combined 4 times in the combiner ring. A detailed description of the combination process can be found in Ref. [10].

2. Stability studies

In order to establish the causes of the variations observed in CTF3 a specialized monitoring tool has been developed. This software tool, which is described in detail in Refs. [11,12], enables on-line observations of the drifts in the machine. It constantly monitors all signals with the possibility to trace back when changes occurred in the machine. It also provides the functionality to observe the correlation between two signals. This tool has been crucial in the work to establish the causes of the drifts and was used for all data acquisition and pre-processing of the data used in this paper.

The following section will explain the cause of the time varying losses in the combiner ring. In Fig. 3 the algorithm to find the cause of the losses is shown. It was found that the losses observed were correlated with the position in a dispersive pickup, as seen in Fig. 4a. The dispersive pickup is located in the transfer line between the linac and the combiner ring with a nominal dispersion of 0.6 m. In order to check that the position change was an energy effect and not an orbit drift the position in a pickup with zero dispersion was also observed. The correlation between the zero dispersion pickup and the losses was indeed small, see Fig. 4b, showing that the losses were linked to the change in energy. In CTF3 the accelerating structures are fully beam loaded. This enables a very high RF to beam efficiency [13]. However, it also means that a variation in current will translate into an energy variation. Therefore, we investigated current fluctuations as a possible source. Fig. 4c shows a correlation plot between the beam current in the linac and the energy, which yields a small correlation factor of $\rho = 0.05$. The energy was measured using a pickup in a dispersive region. The dispersion values were taken from the optics model.

After concluding that the energy variation was not caused by the beam current change in the linac we investigated the correlation of the beam energy with the RF-amplitude. Summing up the variation of the RF-amplitude for the individual klystron and measuring the beam current at each accelerating structure the expected beam energy is calculated. The energy calculated from the RF-amplitude was found to be in good agreement with the energy measured with the dispersive pickup, as seen in Fig. 4d, identifying it as the main cause of the energy fluctuations.

We then aimed to understand the cause of the drift of the RF-amplitude. The RF-amplitude was measured before and after the pulse compression. The variation measured at the klystron output, before the pulse compression, was small compared to after the compression and showed a different behaviour, see Fig. 4f. This

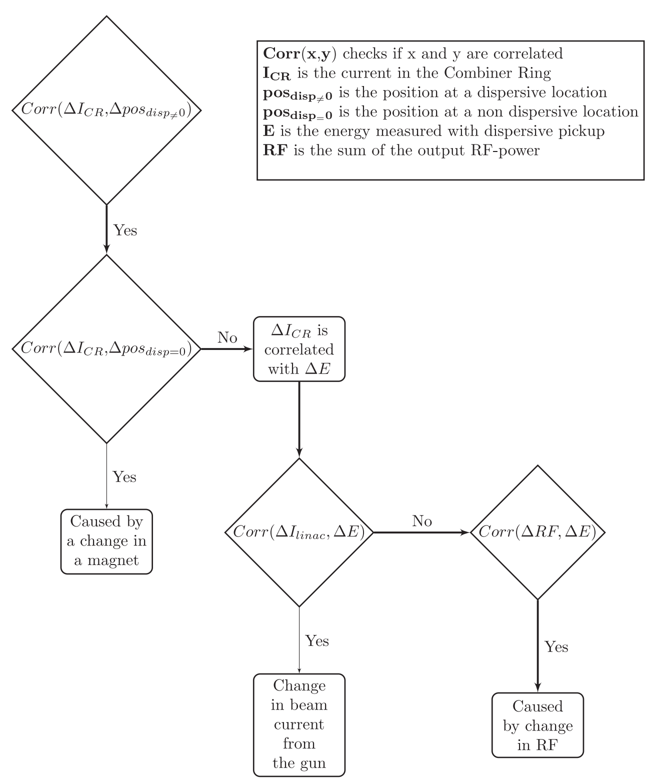

Fig. 3. A flow chart showing the logic in the investigation of establishing the cause of the losses. Each skew square indicates a check of the correlation between two signals. The thicker arrows indicate what was found from the study.

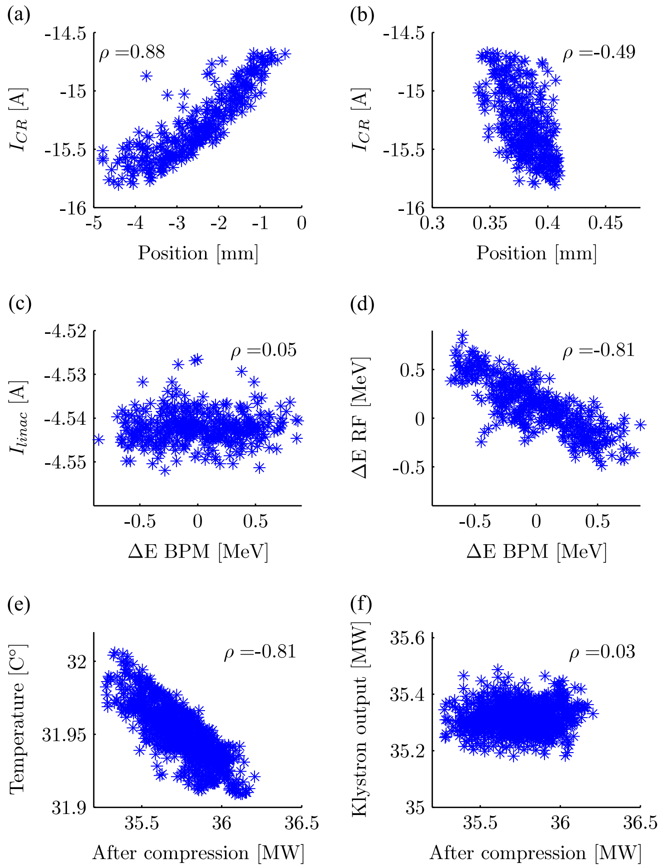

Fig. 4. Plots showing the correlation between different signals in the CTF3 machine. The number displayed in each figure is the correlation factor between the two signals.

showed that the main variation observed was coming from the compression step.

Fig. 4e shows the influence of the cooling water on the RF-amplitude. The temperature is averaged over several measurements to better model the actual temperature of the cavity. The theoretical prediction gives that $\pm 0.03\,^{\circ}$C results in an amplitude variation of $\pm 1\%$ [14]. This is in good agreement with the measured influence of the water temperature on the amplitude. The temperature stabilization is performing according to the specification of the present system. A method using the phase program to further stabilize the RF-amplitude is described in Section 3.

3. RF-Amplitude feedback

The pulse compressor is located after the klystron and is increasing the peak power by storing the energy in the high-Q resonating cavity and then releases it near the end of the klystron output pulse. The pulse length, magnitude of the peak power and the flatness of the pulse can be adjusted by changing the phase program of the klystron, see Fig. 2. It is the parabolic shaped part of the phase program, between B and C in Fig. 2, where the RF-amplitude feedback operates.

3.1. Layout and implementation

The compressed output power is measured and compared to a setpoint. The difference between the setpoint and the measurement is used to calculate the new phase program. It has been observed that the presence of the beam can affect the measurement of the compressed amplitude. In order to avoid these reflections coming from the beam into the RF-amplitude measurement, a RF-pulse offset in time with respect to the beam cycle is measured. This is possible since the klystrons are operated with a higher frequency than the beam.

The new phase program is calculated using the following equation:

$$\Phi_i = \phi_i + g_p(s_i - m_i) + g_m\left(1 + \frac{i}{n}\right)\frac{1}{n}\sum_{j=0}^{n}(s_j - m_j) \quad (1)$$

where Φ is the new phase program, ϕ is the old phase program, g_p is the gain for the point by point correction, m_i is the measured power, g_m is the gain based on the mean difference between the setpoint and the measured, n is the number of samples, i is the index of the phase function, proportional to the time along the pulse, and s is the setpoint.

The first term is correcting on a point by point basis. This means that in case there is a difference between the setpoint and the measured RF-amplitude a change is inferred in the corresponding place in the phase program. The motivation of the second term in the correction is to allow a higher gain of the feedback without introducing extra variation along the pulse. A measurement point at RF-pulse called m_i can be decomposed into the real value: r_i and noise: σ_i. The correction would be $g_p(s_i - m_i) = g_p(s_i - r_i + \sigma_i)$. If $s_i = m_i$ the noise will still be amplified with $g_p(\sigma_i)$. If we instead use the mean difference between the setpoint and the measurement the introduced noise will go down as $1/(\sqrt{n})$. The first term is kept to correct for small changes developing slower like small changes in the shape of the output power from the klystrons.

To avoid correcting in a situation when the klystron is malfunctioning or not at nominal power, values differing more than 7% from the setpoint are ignored when calculating the correction.

3.2. Results

Fig. 5 compares the compressed RF-amplitude when the feedback is turned on and when it is turned off. When the feedback is turned on the long term stability is improved while the pulse to pulse stability remains constant. The pulse to pulse stability is evaluated by calculating the standard deviation of the difference of two consecutive pulses.

Table 1 shows the standard deviation for the compressed pulse with the feedback on and off. All circuits show a clear improvement when the feedback was enabled. The main reason for the different performance of the different circuits, without the feedback, was

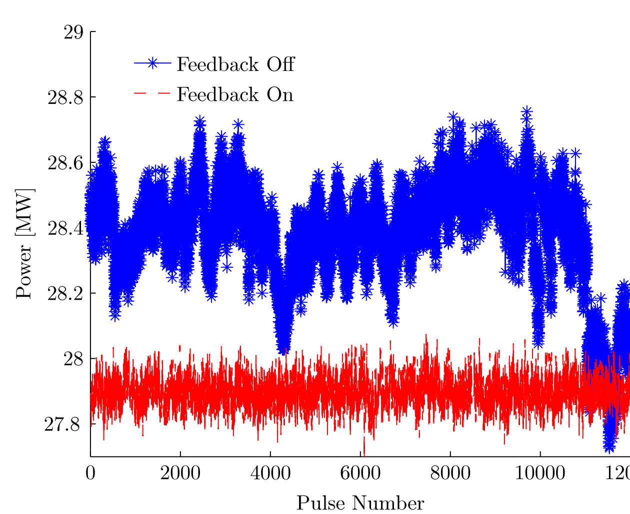

Fig. 5. The compressed RF-amplitude with and without the feedback.

Table 1
Table comparing the standard deviation for the individual circuits when the feedback was enabled and disabled.

Klystron number	σ_{off} (MW)	σ_{on} (MW)	$\frac{\sigma_{off}}{\sigma_{on}}$
Klystron 3	0.121	0.082	1.474
Klystron 5	0.243	0.073	3.324
Klystron 6	0.237	0.065	3.639
Klystron 7	0.272	0.097	2.801
Klystron 11	0.157	0.050	3.156
Klystron 13	0.284	0.100	2.832
Klystron 15	0.060	0.044	1.371

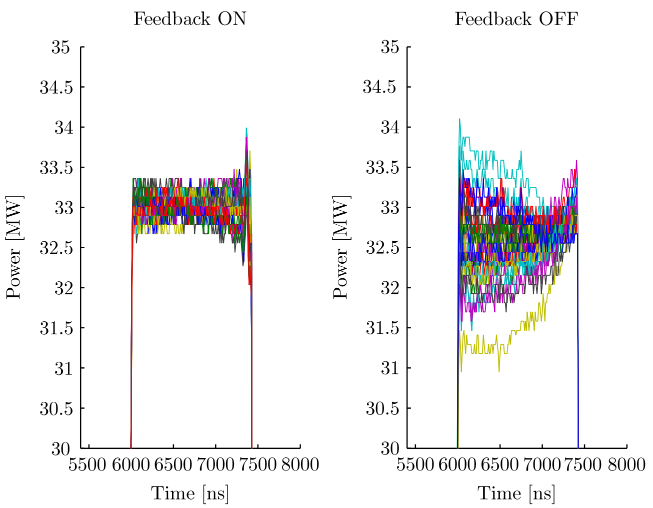

Fig. 6. The RF-amplitude with and without the feedback. The total time for the measurement was 4 h and a trace was saved every fifth minute.

the performance of the water stabilization. The biggest improvement is seen for the worst performing circuits.

Fig. 6 shows the RF-amplitude along the pulse, with and without feedback measuring one pulse every 5 min during 4 h. It is clear that the feedback not only improves the mean RF-amplitude value but also keeps it flatter along the pulse. This is important since a local change in a region of the RF-pulse will result in a change of the beam energy for that part.

Fig. 7 shows the beam energy measured with the dispersive pickup against expectations based on the RF-measurements. The dispersion value at the pickup is taken from the optics model of the machine. In the case when the feedback is off it is close to 1:1 correspondence between the energy measured from the RF-amplitude and from the dispersive pickup. When the feedback is on the energy standard deviation measured at the dispersive pickup is reduced from 0.31 MeV to 0.18 MeV. When the feedback is enabled the expected energy change from the RF-amplitude is reduced by a factor 3 while the one measured from the dispersive pickup is reduced by roughly a factor 2. This is explained by the fact that the change of the phase program also causes a change in the RF-phase. Such phase change with respect to the reference value is compensated by the existing phase-loop acting on every klystron but the correction is not immediate [14]. This also shows that there is margin to further improve the energy stability with other methods.

4. Beam energy feedback

Even with a stable RF-amplitude there is still a small residual variation of energy of ~ 0.2 MeV, as seen in plot 7. A variation of

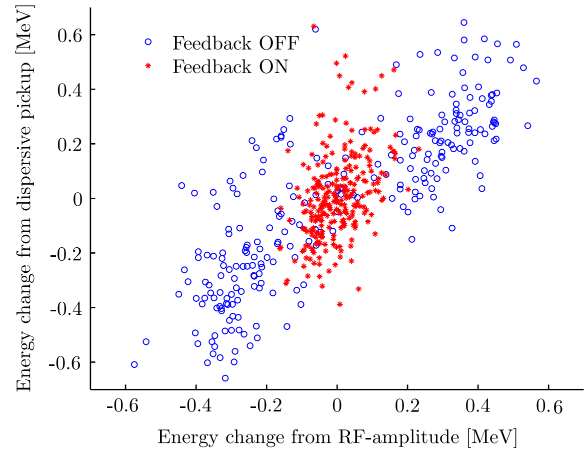

Fig. 7. The change in energy measured with dispersive BPMs plotted against the expected energy change derived from the measured RF-amplitude.

energy is disturbing for beam operation and can, as shown, lead to losses. In order to mitigate this energy variation a feedback designed to measure the energy using a dispersive pickup and change the power of the last klystron in the linac accordingly was designed. A similar approach was used in SLAC, beam line A [15]. However, the method used in SLAC was to change the phase of the klystron to stabilize the energy while in our case we use the phase program to change the RF-amplitude. This method was chosen since changing the phase results in different energy changes to different parts of the pulse due to the static phase sag along the beam pulse, inherently linked to the RF pulse compression. Furthermore it changes the intra-bunch energy spread thus changing the bunch length after passing through the chicane.

4.1. Layout and implementation

In principle it would be possible to calculate the required change of the RF-amplitude from the measured position in the dispersive pickup. However, there are always small uncertainties in the modeled dispersion as well as in the calibration of the RF-amplitude. Instead, we measure the response on the dispersive pickup for each different power level. The method to measure the response is described in the following list:

1. Pre-record phase programs for different output powers of the klystron. This is done by changing the setpoint of the requested power and then applying the algorithm described in Section 3.
2. Send the a phase program corresponding to a certain power level and record the change in position in the dispersive pickup. Before every new RF-amplitude the original power is sent back to store a new starting point. This is done in order to rule out that the energy, and hence the position, has changed in the mean time.
3. A linear interpolation is calculated to get the dependency between the change in power and change in beam energy.

Once the response is recorded it is possible to start the energy feedback. The algorithm of the feedback is shown in Fig. 8. The 3-pulses waiting time is introduced since it takes a few pulses for the control system to change the phase program. The optimization of the gain and the integration period was done using gathered data without the feedback. The figure of merit was the overall standard deviation as well as introduced noise. It was found that an integration period of about 3–4 pulses was the optimum while keeping the gain close to 1. It was also discovered that filtering away bad measurements was essential for a good performance of

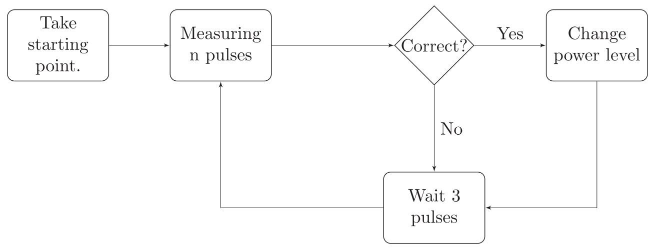

Fig. 8. The layout of the energy feedback.

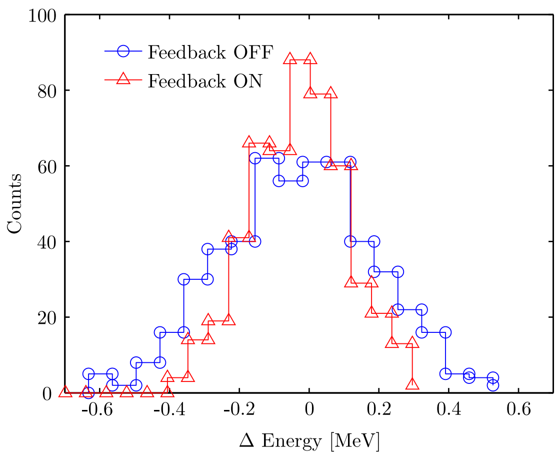

Fig. 9. Example of when the energy feedback is turned on and when it is turned off.

the feedback. The bad measurements points usually come from a bad klystron pulse, for example due to a breakdown. The condition is that the standard deviation cannot be larger than 3 times the standard deviation of the starting points. In case it is bigger than that the measurement is ignored. A cut to deviation larger than 1% of the energy is also applied.

4.2. Results

In Fig. 9 the energy stability when the feedback is on and off is shown. The feedback reduced the standard deviation from 0.22 MeV to 0.13 MeV. This is in good agreement with the predicted corrections from simulations. The standard deviation for the pulse to pulse stability was at this time measured to be 0.09 MeV. The feedback is at the moment limited by the bandwidth. In order to improve this we would need to be able to change the RF-amplitude more frequently. However, this is not possible at the moment due to limitations in the control system.

5. Final results and conclusion

The RF-amplitude feedback plays today an important role for the operation of CTF3. The overall improvement of the two feedbacks working together is almost a factor 3 in energy stability. This is an improvement achieved without adding any extra equipment. The increased energy stability has decreased the losses but also facilitated other studies, e.g. optics studies. The better understanding of the machine from these studies has also increased the acceptance of the machine and hence increased the beam current stability. All this together has enabled a beam current stability for a combined factor 4 beam in the combiner ring below $\sigma_I/I = 10^{-3}$ which is very close to the requirements for CLIC.

Acknowledgment

The authors would like to acknowledge the CTF3-team for their support and patience during the time the feedbacks were implemented. We would also like to thank Frank Tecker for fruitful discussions and suggestions.

References

[1] D. Schulte, et al., Status of the CLIC phase and amplitude stabilization concept, in: LINAC'10, Tsukuba, Japan, 2010, pp. 103–105.
[2] D. Schulte, R. Tomas, Dynamic effect in the new CLIC main linac, in: PAC'09, Vancouver, BC, Canada, 2009, pp. 3811–3813.
[3] A Multi-TEV Linear Collider Based on CLIC Technology, CLIC Conceptual Design Report, Technical Report CERN-2012-007, CERN, Geneva, May 2012.
[4] G. Sterbini, Beam Current Stability in CTF3, International Workshop on Future Linear Colliders, Geneva, Switzerland, 2010. url: ⟨http://ilcagenda.linearcollider.org/getFile.py/access?contribId=375&sessionId=77&resId=0&materialId=slides&confId=4507⟩.
[5] E. Marin, G. Sterbini, TBL Optics Studies, International Workshop on Future Linear Colliders, Granada, Spain, 2011. url: ⟨http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=302&confId=5134⟩.
[6] G. Geschonke, A. Ghigo, CTF3 Design Report. oai:cds.cern.ch:559331, Technical Report CERN-PS-2002-008-RF. CTF-3-NOTE-2002-047. LNF-2002-008-IR, CERN, Geneva, 2002.
[7] J. Mourier, R. Bossart, J.M. Nonglaton, I.V. Syratchev, L. Tanner, Low level RF including a sophisticated phase control system for CTF3, in: LINAC'04, Lübeck, Germany, 2004, pp. 748–750.
[8] R. Bossart, P. Brown, J. Mourier, I.V. Syratchev, L. Tanner, High-Power Microwave Pulse Compression of Klystrons by Phase-Modulation of High-Q Storage Cavities, Technical Report CLIC-Note-592, CERN, 2004.
[9] S.H. Shaker, R. Corsini, P.K. Skowronski, I. Syratchev, F. Tecker, Phase modulator programming to get flat pulses with desired length and power from the CTF3 pulse compressors, in: IPAC'10, Kyoto, Japan, 2010, pp. 1425–1427.
[10] F. Tecker, et al., Bunch frequency multiplication in the CLIC test facility CTF3, in: PAC'03, Portland, USA, 2003, pp. 684–686.
[11] T. Persson, Fighting Beam Instabilities at CTF3, Master's Thesis, Chalmers University of Technology, 2011.
[12] T. Persson, P. Skowronski, Beam stability at CTF3, in: IPAC'12, New Orleans, USA, 2012, pp. 1888–1890.
[13] R. Corsini, et al., First full beam loading operation with the CTF3 linac, in: EPAC'04, Lucerne, Switzerland, 2004, pp. 39–41.
[14] A. Dubrovskiy, F. Tecker, RF pulse compression stabilization at the CTF3 CLIC test facility, in: IPAC'10, Kyoto, Japan, 2010, pp. 3774–3776.
[15] R.L. Cottrell, C.A. Logg, M.J. Browne, Nucl. Instrum. Methods 164 (3) (1979) 405, http://dx.doi.org/10.1016/0029-554X(79)90071-5, url ⟨http://www.sciencedirect.com/science/article/pii/0029554X79900715⟩.