STABILIZATION OF THE BEAM INTENSITY IN THE LINAC AT THE CTF3 CLIC TEST FACILITY

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Abstract

A new electron beam stabilization system has been introduced in CTF3 in order to open new possibilities for CLIC beam studies in ultra-stable conditions and to provide a sustainable tool to keep the beam intensity and energy at its reference values for long term operations. The stabilization system is based on a pulse-to-pulse feedback control of the electron gun to compensate intensity deviations measured at the end of the injector and at the beginning of the linac. Thereby it introduces negligible beam distortions at the end of the linac and it significantly reduces energy deviations. A self-calibration mechanism has been developed to automatically configure the feedback controller for the optimum performance. The residual intensity jitter of 0.045% of the stabilized beam was measured whereas the CLIC requirement is 0.075%.

INTRODUCTION

CTF3 is a test facility, which is extensively used to uncover new frontiers of the Compact Linear Collider (CLIC) and to develop new technologies of normal conducting linear accelerators [1, 2]. In spite that the feasibility of most of the critical CLIC components has been demonstrated the demands on the beam with parameters closer to the CLIC ones are only rising [3]. The quality, the performance and the relevance to CLIC of each beam shot reduces with the beam deviation from the nominal parameters. In CLIC the beam stability and reproducibility are essential properties and they are required in order to keep the maximum luminosity up to 5.9×10^{34} $cm^{-2}s^{-1}$ at energies from 500 GeV to 3TeV during 20 years of high energy experiments [4]. The beam stability in CTF3 needs to be improved in order to meet CLIC requirements.

DRIVE BEAM GENERATION

In CTF3 an electron beam with the intensity of 4.5 A and the pulse length of 1.5 µs is created by a thermionic gun, bunched at 1.5 GHz or 3 GHz in the bunching system and then pre-accelerated up to 20 MeV (see Fig. 1). After the injector the beam passes through the cleaning chicane, where low energy particles are eliminated and the bunch length is reduced. The beam of 4.0 A with a low energy spread is injected into the linac. It is accelerated in the fully loaded mode at the average gradient of 7 MV/m up to 125 MeV. Then the beam goes through the stretching chicane, where the bunch length is increased. After that the beam goes around the delay loop and combiner ring, where the intensity is increased by the factor four or eight. The generated high-intensity, high-energy beam is delivered to the tests lines, where the beam is most required to be stable.

BEAM STABILITY OUTLINES

Beam current variations and drifts at the level of 10^{-4} in CTF3 cannot be associated with any one particular device as dominant source of influence. Apparently, it is a combination of imperfections of all components together: the electron gun, RF sources and the current control of magnets. On top of this each of components changes its properties due to fatigue processes, temperature variations and unknown sources. This study is limited to the consideration of the treatment of integrated deviations only in the linac.

The intensity and energy stabilities are the main properties of the beam, which are responsible for the stable pulse-to-pulse beam combination and delivery to the tests areas. In the fully loaded operation the beam energy deviation at the end of the linac can be approximated as follows:

$$\Delta E \propto -\tfrac{1}{2} I_L \Delta\varphi_L{}^2 - \Delta I_L + \frac{I_L}{E_L}\Delta E_I, \qquad (1)$$

where I_L and φ_L – the intensity and phase at the beginning of the linac and E_I is the energy at the end of the injector. The beam phase and intensity deviations propagate from the injector to the linac and they are coupled through the energy deviation in the cleaning chicane:

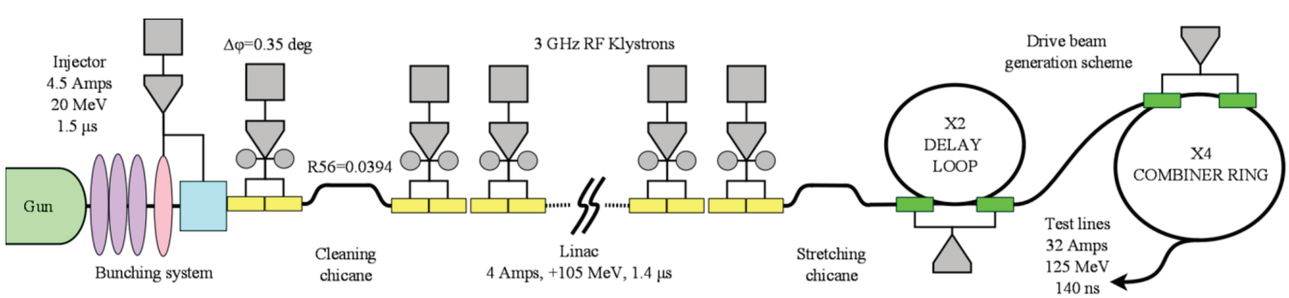

Figure 1: CTF3 layout.

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$$\Delta I_L \approx \Delta I_I \frac{I_L}{I_I} - k\, I_L \frac{\Delta E_I}{E_I}, \quad (2)$$

$$\Delta\varphi_L \approx \Delta\varphi_I + R_{56} f_{RF}/c \frac{\Delta E_I}{E_I}, \quad (3)$$

where I_I and φ_I are the intensity and phase before the chicane, k is the cleaning sensitivity constant corresponding to a ratio of the relative current change through the chicane with a fixed R_{56} to the relative energy deviation, f_{RF} is the linac RF frequency and c is the speed of light. By eliminating the relative energy deviation in the injector $\frac{\Delta E_I}{E_I}$ and substituting Eq. 2 and 3 into Eq. 1 the beam energy deviation ΔE scales with a function of beam current deviations before and after the cleaning chicane.

One option to improve the stability is to keep the intensity stable in the injector ($\Delta I_I = 0$):

$$\Delta E \propto -\frac{\Delta I_L}{I_L}\left(I_L + \frac{E_I\, I_I}{E_L k}\right) - \frac{I_L}{2}\left(\Delta\varphi_I - \frac{R_{56} f_{RF}}{c\, k}\frac{\Delta I_L}{I_L}\right)^2. \quad (4)$$

This option is favourable when the beam energy and phase remain unchanged in the injector. Another alternative option is to keep the intensity stable right after the chicane ($\Delta I_L = 0$):

$$\Delta E \propto \frac{E_I\, I_I}{E_L k}\frac{\Delta I_I}{I_I} - \frac{I_L}{2}\left(\Delta\varphi_I + \frac{R_{56} f_{RF}}{c\, k}\frac{\Delta I_I}{I_I}\right)^2. \quad (5)$$

The second option copes with small energy and intensity variations and it keeps the intensity stable at the end of the linac. An option can be chosen that has the smallest absolute energy deviation. The preference shall be given to the second one if $\left|\Delta E|_{\Delta I_L=0}\right| < \left|\Delta E|_{\Delta I_I=0}\right|$ (Eq. 4 and 5), where the intensity deviations are linked through the Eq. 2. The condition can be resolved for negative deviations only when the phase deviation is small:

$$2|\Delta\varphi_I| < \left|\frac{c\, k}{R_{56} f_{RF}}\right|. \quad (6)$$

When the phase deviation is significantly smaller in the above equation and while keeping the linac intensity stable the total compensation must meet one of the following requirements:

$$-\Delta\varphi_I^{\,2} \gtrsim \frac{\Delta I_L}{I_L} \gtrsim -\left(\frac{c\, k}{R_{56} f_{RF}}\right)^2 \quad \text{or} \quad \frac{\Delta I_L}{I_L} > 0. \quad (7)$$

The third option is to keep the total energy stable $\Delta E = 0$. An approximated solution from Eq. 4 and 5 is to compensate the sum of weighted deviations such that:

$$s\frac{\Delta I_L}{I_L} - (1-s)\frac{\Delta I_I}{I_I} = 0, \qquad s \approx 1 - \frac{E_I I_I}{k E_L I_L + 2 E_I I_I}. \quad (8)$$

Since $\frac{1}{2} < s < 1$ intensity deviations in the linac should also be significantly compensated.

CTF3 BEAM STABILITY

The CTF3 parameters used for the following estimations are shown in the Fig. 1. The cleaning sensitivity k can be estimated from the injector beam energy distribution function as a derivative at the cut-off energy level. It can also be measured as a ratio of the beam loss after the chicane to the injector energy change by the control of the RF field level in the last two accelerating structures. The cleaning sensitivity $k = 0.5$ was measured in a setup with a high energy acceptance, in the nominal setup the value is supposed to be higher.

The lower injector phase error is bound by the RF phase stability. All RF phases in accelerating and bunching cavities are locked by RF phase loops, which are stabilizing phases at the level of the minimum RF phase shifters step $\Delta\varphi_{RF}$ [5]. Thereby the injector phase error should be at least as $2\Delta\varphi_{RF} < \sup \Delta\varphi_I$. For the same reason the current reference can be established with an error given by the phase. Taking into account the above the criteria to compensate the intensity variations in the CTF linac can be derived from Eq. 7 as:

$$\left|\frac{\Delta I_L}{I_L}\right| \gtrsim 0.015\%. \quad (9)$$

The upper compensation limitation is restricted naturally by the performance of the thermionic gun and transient losses.

One of the current CTF3 goals is to establish a highly stable combined beam in terms of the energy and intensity at the same time: $\left|\frac{\Delta I_L}{I_L}\right| < 0.075\%$ and $\left|\frac{\Delta E}{E}\right| < 0.1\%$. For this type of operation an intermediate option should be chosen between the stable intensity (Eq. 5) and the stable energy with $s \approx 0.769$ (Eq. 8), where residual energy deviations should come only from beam phase deviations.

The proposed three options to keep the beam intensity stable give different energy deviations at the end of linac (see Fig. 2). Medium term observations of intensities showed very small deviations in the injector while the deviations in the linac were up to $\pm 0.4\%$. Thus the first option with the stable injector represents the current status with no compensation, where the energy deviation proportionally grows with the intensity deviation reaching levels over 0.6%. The second option with the stable linac should bring intensity deviations in the linac to zero and reduces energy deviations down to 0.2%, which is above the required value. The third option with the stable energy

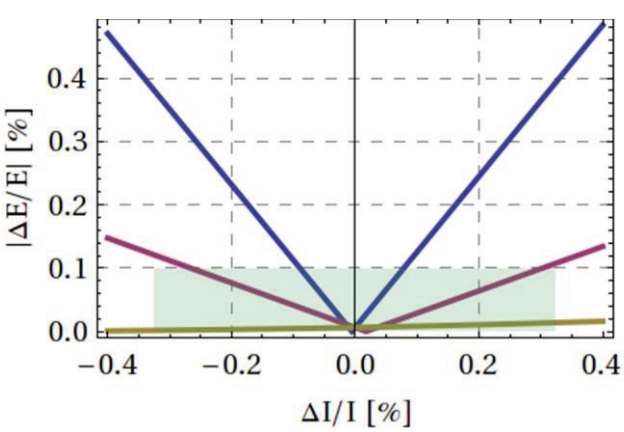

Figure 2: Total energy deviations at the end of the linac with corresponding intensity changes in the linac: blue line - stable injector, purple line – stable linac and yellow line – stable energy. The parts of the lines lying in the shaded area satisfy the stability goal.

at the end of the linac should bring deviations close to the requirements for both parameters.

DEVELOPED SOLUTION

In order to apply different intensity compensation options a beam feedback software system has been developed and integrated into the control system in CTF3. In all cases the actuator of the intensity compensation is the grid voltage control in the thermionic gun. The gun control allows modifying the beam intensity in the order of 10^{-5} Amps, which is sufficiently small. The beam intensity is measured by Beam Position Monitors (BPM) with a resolution of only 5.8 mA, which is more than 0.1%. The integration over the pulse length up to 1.4 µs and averaging over several consecutive BPMs improve the resolution and reduce the noise down to 0.3 mA, which is below 0.01%. For each mode of operation a set of BPMs and their weights are predefined, and they are used to calculate the weighted mean intensity. The calculated intensity is compared with the reference value specified by operators. Based on this information the controller estimates the needed gun voltage correction and applies it on the next pulse (see Fig. 3). In order to prevent strong or unnecessary influence on the beam energy the upper and lower deviation thresholds are respected (for example see Eq. 9). The best and sustainable feedback performance has been achieved by applying exponential moving average filter on the weighted mean intensity, which also prevents from undesirable additional high-frequency fluctuations.

CALIBRATION

A self-calibration process of the feedback controller has been implemented to automatically compute most of the controller parameters. It provides an accurate calibration for the optimum performance. Inaccurate settings may lead to oscillation around the reference value, a large correction time or overshoots of the beam current. In the calibration mode the gun voltage is applied in a predefined pattern and the beam current is logged to determine the beam response, the noise impact, control limitations, setup correctness and the best filter parameter. It can be carried out at any time after significant modifications in the injector setup or in the cleaning chicane or when the controller is losing its efficiency due to some slow processes.

CONCLUSIONS

The intensity stabilization system has been successfully developed in a way to minimize energy deviations by keeping the intensity stable. It was tested and used during the normal operation and during the night operation in CTF3. The implemented self-calibration process allows operatively adapting to new setups with the best performance. Using the developed system the beam intensity has been stabilized in the injector down to 0.045%, which improves the earlier result of 0.05%. The intensity stabilization in the linac successfully transfers

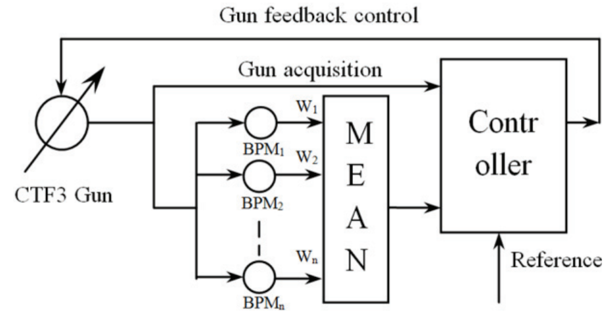

Figure 3: Intensity control layout.

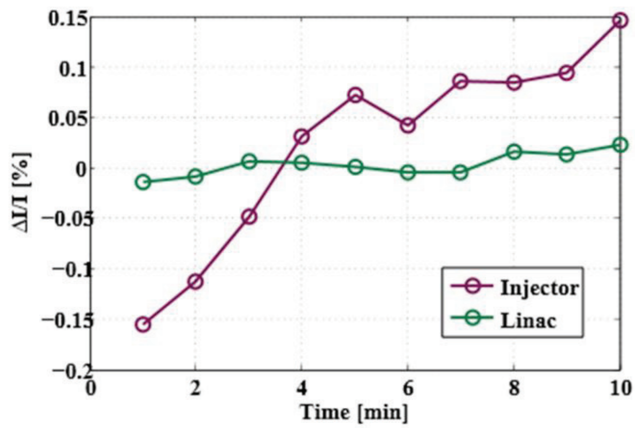

Figure 4: Illustration of the stabilization of the intensity in the linac by adjusting the intensity in the injector.

intensity variations over 0.15% from the linac into the injector within a small and preserved range of gun adjustments (see Fig. 4). Thereby it keeps the intensity stable at the end of the linac and it notably reduces energy deviations.

The effect of the stabilization system on possible changes of the emittance and bunch length must be additionally studied. Explicit energy correlation measurements will be performed soon.

The approach to cure integrated beam errors has been demonstrated to be a feasible and efficient technique at the cleaning chicane in CTF3 by transferring intensity variations from the linac into the injector.

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