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TOWARDS STABLE ACCELERATION IN LINACS

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Abstract

Ultra-stable and -reproducible high-energy particle beams with short bunches are needed in novel linear accelerators and, in particular, in the Compact Linear Collider CLIC. A passive beam phase stabilization system based on a bunch compression with a negative transfer matrix element R_{56} and acceleration at a positive off-crest phase is proposed. The motivation and expected advantages of the proposed scheme are outlined.

INTRODUCTION

In the Compact Linear Collider (CLIC) the beam phase and energy stability and reproducibility are essential properties in its mission to successfully and precisely study electron-positron collisions and reach the maximum luminosity up to 5.9×10^{34} $cm^{-2}s^{-1}$ at energies from 500 GeV to 3TeV [1]. Future Free Electron Lasers and Energy Recovery Linacs require even a better beam stability. The common dominant source of beam jitter is the voltage jitter of klystron-modulators passing through the klystron and RF systems. In order to reach the beam phase stability of 0.05º at 1 GHz the high-voltage stability of CLIC klystron-modulators is currently required to be better than 3×10^{-5}, which has not achieved yet. In this paper a passive beam phase and energy stabilization scheme, which allows significantly relaxing the requirement, is introduced and the first results obtained in the CLIC test facility CTF3 are presented.

KLYSTRON RF STABILITY

The transfer function of klystron output RF field variations as reactions to small ($\Delta V_{kly}/V_{kly} \ll 1$) and slow ($|s| \ll 2\pi f$) klystron voltage variations can be approximated as a function $H(s) \approx \frac{k_a}{2} + i\left(2\pi k_p + |s| k_p^*\right)$, where f – the RF frequency, V_{kly} – the klystron high-voltage and k_a, k_p and k_p^* are the sensitivity parameters defined and discussed in this section.

The klystron beam is produced by a thermionic cathode and accelerated by high-voltage electrodes. The beam current is determined by the klystron voltage and given by Child's law for space-charge limited, non-relativistic electron beams:

$$I_{kly} = K \cdot V_{kly}^{3/2} , \qquad (1)$$

where I_{kly} is the produced DC beam current and the perveance K is a geometrical property of the gun. This beam sequentially passes through an input resonant cavity, where the LLRF is applied, and several "penultimate" cavities connected by drift tubes, where the beam bunches. At the last output cavity bunches decelerate generating the high-power RF field, which is coupled out to an RF transmission line. By definition, the klystron efficiency is given by:

$$\eta_{kly} \equiv \frac{P_{rf}}{I_{kly} V_{kly}} = \frac{P_{rf}}{K \cdot V_{kly}^{5/2}} , \qquad (2)$$

where P_{rf} is the output RF power. The efficiency and its sensitivity to the klystron voltage can be estimated by measuring the voltage, current and output RF power at different voltage levels. From Eq. 2 the RF power sensitivity to the klystron voltage change can be defined as the following:

$$k_a = \left(\frac{\Delta P_{rf}}{P_{rf}}\right) \Big/ \left(\frac{\Delta V_{kly}}{V_{kly}}\right) \approx \frac{5}{2} + \left(\frac{\Delta \eta_{kly}}{\eta_{kly}}\right) \Big/ \left(\frac{\Delta V_{kly}}{V_{kly}}\right) , \qquad (3)$$

where ΔV_{kly} is a small constant voltage offset and the perveance sensitivity is neglected since it is significantly smaller than the other components.

When the growth of the beam harmonic current is given by the "ballistic" model, the first harmonic of the current density determines the output RF [2]. In particular, the phase of the density oscillation of $\frac{2\pi f L_{kly}}{\beta c}$, where L_{kly} – the distance between the input and output cavities, β – the relative speed of electrons and c –the speed of light, gives an estimation of the output RF phase sensitivity to the klystron voltage change:

$$k_p = \left(\frac{\Delta \varphi_{rf}}{2\pi}\right) \Big/ \left(\frac{\Delta V_{kly}}{V_{kly}}\right) \approx - \frac{f L_{kly}}{c\sqrt{\frac{V_{kly}}{m_e}\left(2+\frac{V_{kly}}{m_e}\right)^3}} , \qquad (4)$$

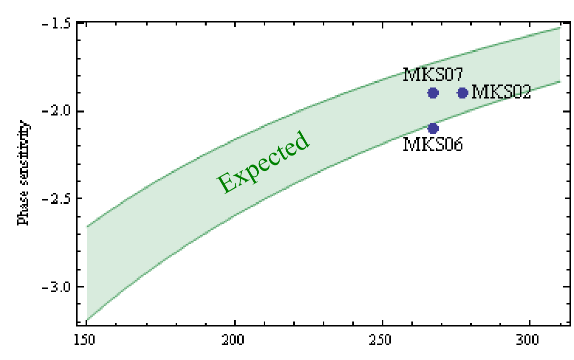

Figure 1: Measured RF phase sensitivities to the klystron voltage of three klystrons Thales-2132 ($L_{kly} \approx 55\ cm$, $f \approx 3\ GHz$). Blue dots – the measurements, the green area – estimated sensitivities using Eq. 2.

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where m_e is the electron rest mass (see Fig. 1). A constant voltage gradient gives the same phase change as a frequency detuning of resonant cavities of $\frac{\delta\omega}{\omega_0} = -L_{kly}/c\beta^2\beta'$. The RF phase sensitivity to the klystron voltage gradient can be estimated as the following:

$$k_p^* = \left(\frac{\Delta\varphi_{rf}}{2\pi}\right) \Big/ \left(\frac{V'_{kly}}{V_{kly}}\right) \approx -\frac{Q_{kly}}{\pi f} k_p \ , \qquad (5)$$

where Q_{kly} is a generalized Q-factor of the klystron.

For voltage deviations $\Delta V_{kly}/V_{kly} \ll 1$ in a flat voltage region normalized deviations of the complex RF field $E = \sqrt{P_{rf}} e^{i\,2\pi\varphi_{rf}}$ are given by $\frac{\Delta E}{|E|} = \frac{|\Delta E|}{|E|} e^{i\left(\frac{\pi}{2} - \alpha_{rf}\right)}$, where:

$$\tan\alpha_{rf} \approx \frac{k_a}{4\pi k_p} \ , \qquad (6)$$

$$\frac{|\Delta E|}{|E|} \approx \sqrt{{k_a}^2 + \left(4\pi k_p\right)^2} \frac{\Delta V_{kly}}{V_{kly}} \ . \qquad (7)$$

The measured and expected pulse-to-pulse RF stabilities of one of CTF3 klystrons Thales-2132 is shown in Fig. 1. A complex normal distribution perfectly fits the measured deviations. The principle vector of the distribution, the standard deviation along this vector is the biggest, coincides with the estimated vector using Eq. 6-7 in the angle and almost in the length equivalent to three standard deviations. The LLRF, signal noises and

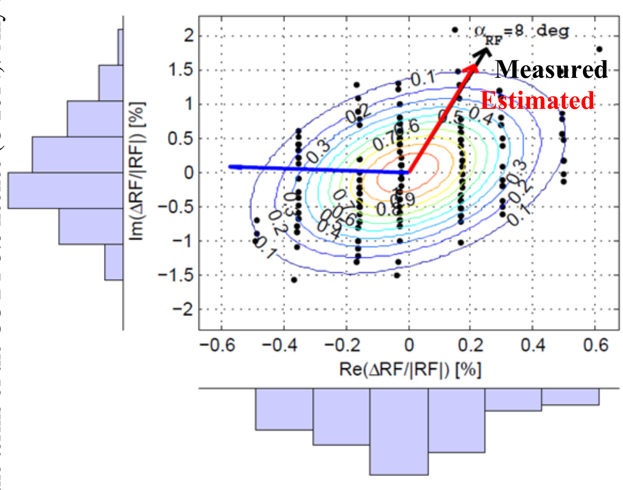

Figure 2: Pulse-to-pulse klystron RF stability. Klystron model is Thales-2132 ($V_{kly} \approx 270.1\ kV$). Black dots - measured complex RF deviations of 208 pulses, the ellipses - the probability density function of the fitted complex normal distribution, the standard deviation of the distribution along the black (blue) vector is the biggest (smallest) and its length equals to three standard deviations, the red vector calculated using Eq. 6 and 7 whose length also equals to three standard deviations. The sensitivity parameters and voltage stability were measured independently: $k_a \approx 3.5$, $k_p \approx -2.2$ ($k_p \approx -2.1$ from eq. 4) and $\Delta V_{kly}/V_{kly} \approx 4.5 \cdot 10^{-4}$.

detuning due to the voltage gradient (Eq. 5) were identified to be the sources of discrepancies between the expectation and measurements and of non-negligible residual components. The measurements of the RF stability within the pulse showed similar distributions, which indicates that the source of pulse-to-pulse and in the pulse fluctuations is the same and the dominant part of it is induced by the klystron voltage (Fig. 3).

RF PULSE COMPRESSION

Klystrons, for example in CTF3 and SwissFEL, are equipped with RF pulse compression cavities (so called LIPS- and BOC-cavities) in order to gain in peak power. The klystron RF pulse is fed into resonant cavities, where the RF field is stored until a certain moment, and then the input field sums with the stored at the output port. An equivalent circuit [3] was studied in order to estimate the output deviations as a function of klystron RF deviations. In general, since the system is linear and time-invariant, the output deviation is independent of the static part of RF pulse. But since the transfer characteristic depends on the time, a single frequency deviation results in a spectrum. The important part for the beam spectrum corresponds to only a part of the time interval near the RF output peak power. The numerical simulations of the circuit model with parameters close to one of the CTF3 compressors showed that the parameter α_{rf} changes along the compressed part of the pulse by less than <0.1° for voltage oscillations whose frequencies are below 50 MHz and voltage oscillations induced by frequencies above 50 MHz should be significantly suppressed in the compression system. However, the oscillations of LLRF can significantly change the distribution of RF output deviations. In CTF3 the region of high spectral densities of the RF klystron jitter (see Fig. 3 B) were measured

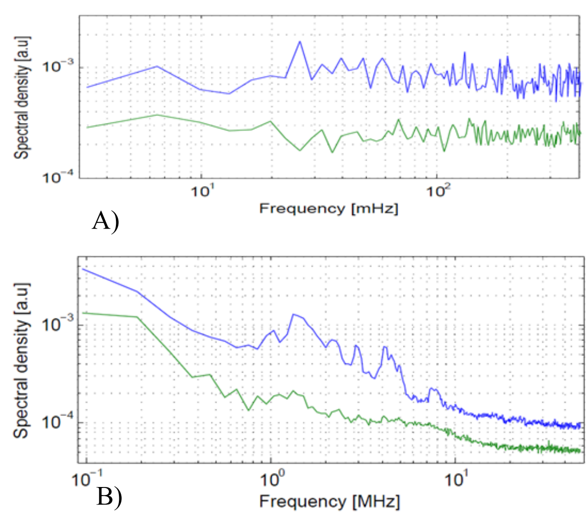

Figure 3: Measured spectral densities of the klystron output normalized RF jitter. Blue lines correspond to the jitter collinear with those that are induced by the klystron voltage, green lines – all the others. The plot A shows the pulse-to-pulse offset jitter and the plot B shows the fast jitter along the pulse.

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below 10 MHz. Numerical simulations showed that the klystron RF jitter passing through the RF compressor preserves the strong phase-amplitude RF correlation induced by the klystron voltage. The result was also confirmed by the measurements.

POSITIVE OFF-CREST ACCELERATION

Let a longitudinally normally distributed bunch with a normal deviation of σ_b passes through an accelerating structure at a mean off-crest RF phase of φ_b (see Fig. 4). And let the stored RF field in the structure randomly changes due to only a slow klystron voltage jitter and with a normal deviation of $\sigma_{rf} = \frac{|\mathrm{std}\,E|}{|E|}$, which can be estimated using Eq.7. Then the expected normalized standard deviation of the distribution of particles' energy gain deviations is given by:

$$\frac{\langle\sigma_A(E)\rangle}{\langle E\rangle} = \frac{\sigma_{rf}}{\sqrt{2}}\sec\varphi_b\sqrt{e^{\sigma_b^2} - e^{-\sigma_b^2}\cos 2(\varphi_b - \alpha_{rf})}\ .(8)$$

Solving Eq. 8 for short bunches ($\sigma_b \ll 1$ rad) the bunch energy jitter reaches its minimum level at a positive off-crest acceleration phase of $\varphi_b \approx \alpha_{rf}$:

$$argmin_{\varphi_b}\frac{\langle\sigma_A(E)\rangle}{\langle E\rangle} \approx \alpha_{rf}\ ,\quad min_{\varphi_b}\frac{\langle\sigma_A(E)\rangle}{\langle E\rangle} \approx \sigma_{rf}\sigma_b\ . \quad (9)$$

If the klystron is operated at its peak efficiency level the phase φ_b can be calculated using the following equation:

$$\varphi_b \approx atan\left(\frac{5c}{8\pi f L_{kly}}\sqrt{V_{kly}/m_e\left(2+V_{kly}/m_e\right)^3}\right). \quad (10)$$

PASSIVE BEAM PHASE STABILIZATION

The positive off-crest acceleration is the effective way to keep the bunch energy stable only if the bunch phase is stable. The RF system in case of the bunching system based on the velocity modulation and laser phase jitters in case of photo-injectors are the prime sources of bunch phase jitter in injectors. A bunch compression arc or chicane with a negative R_{56} ($\delta z/\delta p < 0$) can significantly correct it before the bunch reaches the main linac (see Fig. 5) if the bunch is pre-accelerated at a positive off-

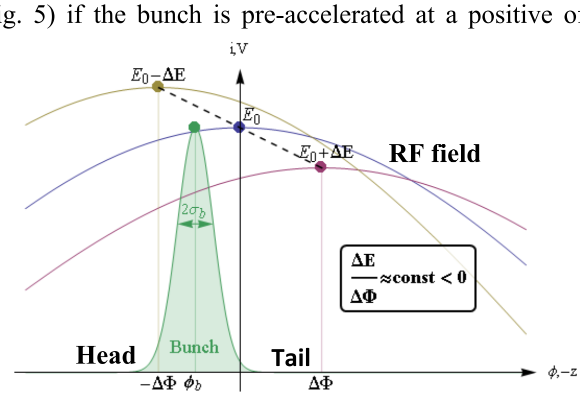

Figure 4: Illustration of a bunch acceleration by RF fields produced by a klystron with small voltage deviations.

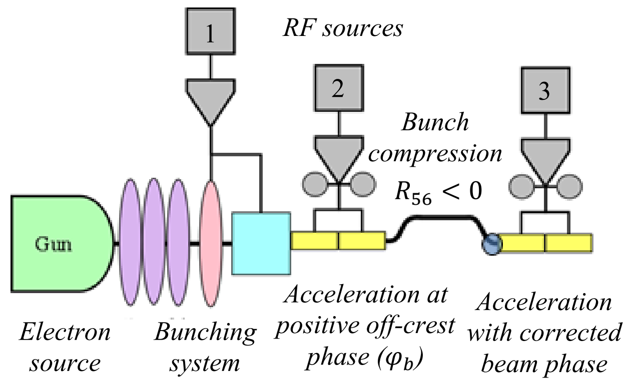

Figure 5: Layout of an injector with the passive beam phase stabilization system.

crest phase of $\varphi_b \approx \alpha_2$ and

$$R_{56} \approx -\frac{c(E_1+E_2)}{2\pi f(E_1\tan\alpha_1 + E_2\tan\alpha_2)}\ , \quad (11)$$

where E_1 is the energy gain in the bunching system, E_2 is the energy gain during the pre-acceleration phase, α_1 and α_2 are the RF jitter phase-amplitude correlation angles (Eq. 6) of the bunching and pre-acceleration klystrons respectively. In case of a simple photo-injector $\alpha_1 = 0$. In order to archive the best performance the R56 in Eq. 11 must be tuned taking into account the non-relativistic effects, wake-fields in accelerating structures and space charges. First numerical studies showed that the CLIC beam phase stability of 0.05° at 1 GHz can be achieved using klystron-modulators with a voltage stability of only 50×10^{-5} instead of the current requirement of 3×10^{-5}.

CONCLUSION

In CTF3 the study and measurements of klystron RF stability revealed that the dominant source of the RF jitter is the klystron-modulator voltage jitter, which induces phase-amplitude correlated RF deviations (see Eq. 6,7). In linacs the acceleration at the positive off-crest phase (see Eq. 9) significantly reduces the beam energy jitter and the passive beam stabilization using a bunch compression like an arc or chicane with negative R_{56} (see Eq. 11) corrects the beam phase jitter after the bunching system.

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