

# PULSE COMPRESSOR PHASE AND AMPLITUDE MODULATION BASED ON ITERATIVE LEARNING CONTROL\*

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## Abstract

This paper presents an alternative way to produce flat-topped RF pulses at the pulse compressor output. Flat-topped RF pulses are suitable for multi-bunch operation where it is often required that beams experience the same accelerating gradient. Moreover, the energy gain, in this case, is less sensitive to timing jitters. The proposed approach is based on Iterative Learning Control technique, which iteratively updates the input waveforms, in order to generate the desired output waveforms.

## INTRODUCTION

The SwissFEL machine, currently being constructed at Paul Scherrer Institut, will provide a source of very bright and short X-ray pulses. The SwissFEL C-band (5.712 GHz) Linac consists of 26 Radio Frequency (RF) stations. Each station is composed of a single klystron feeding an RF pulse compressor and four accelerating structures. The pulse compressor designed for the SwissFEL is based on a single Barrel Open Cavity (BOC) which inherently has a high quality factor resulting in a significant energy storage capacity and a relatively long filling time [1]. In the original form of pulse compression, which is commonly referred to as the “phase jump” regime, the input phase flips by 180°, generating a reflected wave transient into the acceleration structure. This high power transient decays relatively slowly giving the RF structure time to build up an accelerating gradient higher than possible from the klystron alone. However, this RF pulse shape is not suitable for multi electron-bunch operation where it is often required that all electron bunches see the same amplitude and phase in the accelerating structure. More complicated operation modes are also possible by reversing the phase very slowly which is referred to as the “phase modulation”. With a continuously modulated phase, the BOC output peak amplitude is lowered and flattened [2]. The SwissFEL RF drives operate in a pulsed mode at the rate of 100Hz, using normal conducting accelerating structures. The RF pulse length is of the order of 1-3μs and no digital RF feedback loop is run within a pulse. Iterative learning control (ILC) is a control technique for systems that operate in a repetitive manner [3]. In this method, the measured waveform or trajectory is compared to the desired one to give an error estimate, which is then used to update the inputs for the next run. Therefore, for our problem, i.e. controlling the pulse shape, an iterative approach is a good candidate. Previously in [4], a model-free ILC algorithm was employed

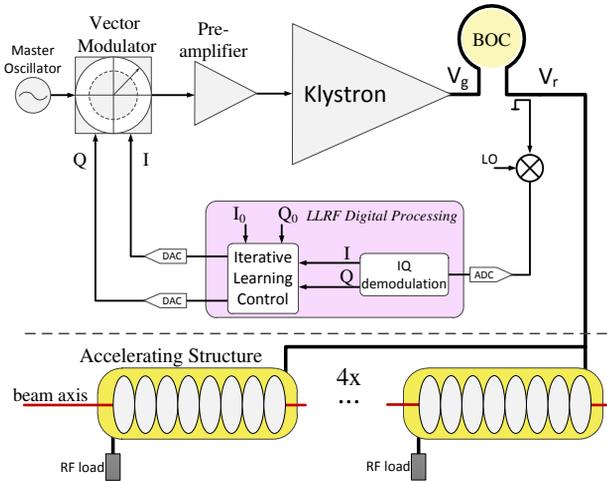


Figure 1: The simplified RF layout of a C-band RF station in the SwissFEL beamline.

to flatten the klystron RF pulse. In this paper, an ILC-based approach for producing flat-topped RF pulse is introduced, which modulates both input phase and amplitude waveforms. This method has been successfully applied on the RF pulse compressor at the SwissFEL Linac test facility.

## SYSTEM DESCRIPTION

The layout of a C-band RF station is illustrated in Fig. 1. The RF signal source (5.7 GHz) is generated by a master oscillator. The discrete sequences of the in-phase,  $I$ , and quadrature,  $Q$ , components of the RF signal are fed into the vector modulator to be up-converted. Each sequence contains 2048 samples with sampling time of  $T_s = 2.4$  ns. The RF signal drives the klystron and finally, the high power RF signal is split over four accelerating structures. The measured  $I$  and  $Q$  waveforms are used in the ILC controller to produce the next  $I$  and  $Q$  inputs to the Digital-to-Analog Converters (DAC). The control objective is to make flat amplitude and phase pulses at the output of the pulse compressor.

### The Pulse Compressor Model

The relation between klystron and pulse compressor voltage is given by [2]

$$\alpha V_g = V_c + \tau \dot{V}_c, \quad (1)$$

where  $V_g$  and  $V_c$  are respectively the klystron and pulse compressor voltage phasors.

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Furthermore,  $\alpha = \frac{2\beta}{\beta+1}$ , and  $\beta$  is the coupling coefficient and  $\tau$  is the filling time of the pulse compressor:

$$\tau = \frac{2Q_0}{(\beta + 1)\omega_0}, \quad (2)$$

where  $Q_0$  is the unloaded quality factor of the pulse compressor and  $\omega_0$  is the angular frequency of the RF wave. To derive equation 1, it has been assumed that the unloaded quality factor is high. Thus  $1/\omega_0$  can be neglected with respect to  $\tau$ . Furthermore,  $V_g$  is assumed to be constant or to change smoothly (i.e.  $\dot{V}_g \ll \omega_0$ ).

For the case where there is a difference between the pulse compressor resonant frequency and the RF wave frequency, Eq. 1 is replaced by the following equation:

$$\alpha V_g = V_c(1 + j\tau\Delta\omega) + \tau\dot{V}_c, \quad (3)$$

where  $\Delta\omega = \omega_0 - \omega_c$ , and where  $\omega_c$  is the nominal angular resonant frequency of the pulse compressor. This frequency difference is introduced to remove the residual phase modulation as described in [2] by operating the klystron with a lower frequency than of the accelerating structure. We refer to this as detuning the BOC. The reflected wave from the pulse compressor, given by  $V_r = V_c - V_g$ , is specified as the output voltage phasor which corresponds to the voltage fed to the accelerating structure. The reflected voltage is the quantity that we are interested in.

## ITERATIVE LEARNING CONTROL

Discretizing equation 3 with Euler backward method ( $T_s \ll \tau$ ) and taking the Z-transform, gives the following transfer function, relating the klystron voltage to the output voltage of the BOC:

$$G_{BOC}(z) = \frac{V_r(z)}{V_g(z)} = \frac{T_s(\alpha - 1) - \tau - jT_s\tau\Delta\omega + \tau z^{-1}}{T_s + \tau + jT_s\tau\Delta\omega - \tau z^{-1}}, \quad (4)$$

where  $T_s$  is the sampling time. We model the RF drive chain as a 1st-order low pass system with a bandwidth determined by  $\gamma$  and a complex scalar gain  $K$ . Therefore, the total transfer function from input to the system (DACs) to the output voltage of the BOC is modeled as,

$$G(z) = K \frac{1 - \gamma}{1 - \gamma z^{-1}} G_{BOC}(z). \quad (5)$$

Using the lifted system representation, the output I and Q signals are generated as follows,

$$y_I + jy_Q = G_{IQ}(u_I + ju_Q), \quad (6)$$

where  $G_{IQ}$  is the lower-triangular Toeplitz matrix of the impulse response  $h(k)$  derived from equation 5, i.e.,

$$G_{IQ} = \begin{pmatrix} h(1) & 0 & \cdots & 0 \\ h(2) & h(1) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ h(N) & h(N-1) & \cdots & h(1) \end{pmatrix}, \quad (7)$$

where  $N$  denotes the number of samples in the flat-topped region.

The  $G_{IQ}$  can be split into real and imaginary parts as  $G_{IQ} = G_r + jG_i$ , where  $G_r$  and  $G_i$  are real matrices. Hence, the system dynamics are given by

$$y = Gu, \quad (8)$$

where,

$$y := \begin{pmatrix} y_I \\ y_Q \end{pmatrix}, \quad u := \begin{pmatrix} u_I \\ u_Q \end{pmatrix}, \quad G := \begin{pmatrix} G_r & -G_i \\ G_i & G_r \end{pmatrix}.$$

To identify signals from different iterations, signals are indexed with iteration counter as subscript. The pulse flatness objective at iteration  $i + 1$ , can be expressed in terms of the following cost function,

$$J_{i+1}(u_{i+1}) = \|y_d - y_{i+1}\|_Q^2 + \|u_{i+1} - u_i\|_R^2, \quad (9)$$

where  $\|\cdot\|$  are the weighted norms, and where  $y_d$  denotes the desired output vector which is given by the desired I and Q waveforms:

$$y_d = \begin{pmatrix} y_{dI} \\ y_{dQ} \end{pmatrix} = \begin{pmatrix} a_d \cos \varphi_d \\ a_d \sin \varphi_d \end{pmatrix}, \quad (10)$$

where  $a_d$  and  $\varphi_d$  are respectively the desired output amplitude and phase in the flat-topped region. We choose a constant  $\varphi_d$  over the flat-topped region, while the desired amplitude is smoothed and thus time-dependent (see [4]).

Taking the derivative of (9) with respect to  $u_{i+1}$  and set it to zero, gives the the optimal input for the next iteration:

$$u_{i+1} = u_i + (R + G^T Q G)^{-1} G^T Q (y_d - y_i) \quad \forall i \geq 0. \quad (11)$$

In order to reduce the computational burden we take the weight matrices,  $R$  and  $Q$ , constant. Thus, the inverse of the matrix is calculated once and stored.

## EXPERIMENTAL RESULTS

For the experiment, the pulse compressor is detuned, as per (3), with the parameters given in Table (1). The iterative learning algorithm is initialized with the phase jump mode. That is, the input amplitude is constant over length N with the phase flipped by  $180^\circ$ . The input phase waveform is iteratively modified from a rapid  $180^\circ$  phase step to a smoothly reversed phase (similar to the phase modulation regime). Here, the klystron amplitude is slightly below the saturation to give an enough headroom for the amplitude modulation. Between each iteration, 10 output waveforms are captured and filtered to suppress the noise. Since at each iteration the shape of the amplitude waveform changes, some amount of time is needed for the BOC temperature controller to stabilize the temperature. Figure 2 shows the experimental result of ILC-based method after 20 iterations and the comparison with the phase modulation approach. In the phase modulation, the input phase waveform is analytically

Table 1: Experiment Parameters

Parameter	value
$\beta$	10.33
$Q_0$	220085
$\omega_0$	$2\pi \times 5.712$ GHz
$\tau$	$1.086 \mu s$
$\gamma$	0.7
$\Delta\omega$	250 kHz
$T_s$	4.2 ns
$N$	120

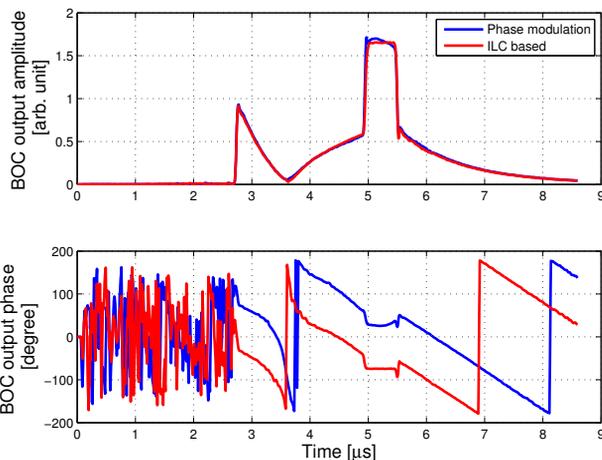


Figure 2: The comparison of ILC-based and the phase modulation approach for the detuned pulse compressor.

derived (see [2]). The converged input amplitude and phase waveforms are depicted in Fig. 3. The amplitude setpoint is chosen to be close to the amplitude in the phase modulation method. According to Fig. 3, there is no significant change in the input average power. Figure 4 illustrates the standard deviation of amplitude and phase pulses over the flat-topped region, for different number of iteration. Comparing the performance of the two methods, the relative standard deviation of amplitude is reduced by a factor of 9 and for the phase by a factor of 12 in the ILC-based approach. In the proposed ILC-based pulse flattening, in contrast to the phase modulation regime which is open-loop, the klystron amplitude is also modulated.

## CONCLUSION

We proposed an iterative learning approach in which the measured  $I$  and  $Q$  waveforms at the BOC output are used to estimate the error of flatness. The algorithm iteratively corrects the input  $I$  and  $Q$  waveforms for the next pulse. The reason of using  $I$  and  $Q$  instead of amplitude and phase is because the system dynamics are close to linear with respect to  $I$  and  $Q$  signals. In the proposed ILC-based pulse flattening, in contrast to the phase modulation regime which

is open-loop, the klystron amplitude is also modulated. The simulation shows that the energy gain drops by nearly 20%

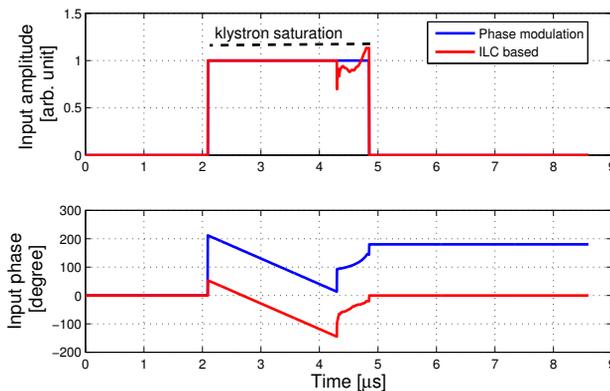


Figure 3: The klystron input amplitude and phase waveforms for phase modulation regime (in blue), and the ILC-based method (in red) after 20 iterations.

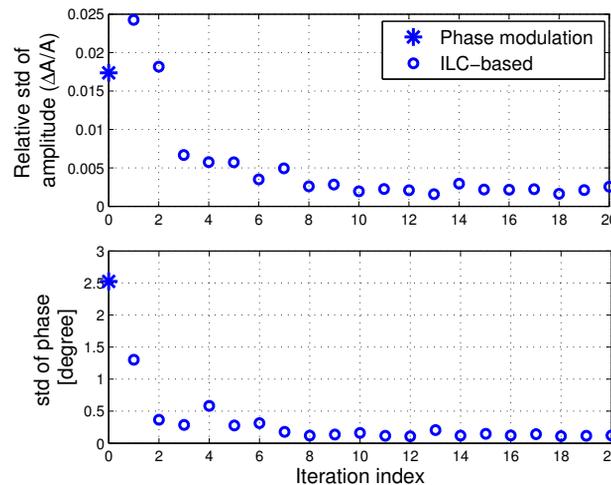


Figure 4: The standard deviation of the BOC output RF amplitude and phase waveforms over the flat-topped region.

in the flat-topped RF pulse regime compared to the phase jump regime.

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