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Optimal Control of Gains in a Linear Accelerator: A Supervisory Method for Vector-Sum Control

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Abstract—In a linear accelerator, driven by radio frequency (RF) amplifier stations, one must precisely control the energy gain of the accelerating beam. The RF stations can be viewed as amplifiers placed sequentially to accelerate the beam. This brief presents two control schemes within which the RF stations act as actuators, and a centralized control unit controls the beam energy by acting either on the RF amplitudes or on the RF phases. The control algorithms are based on convex optimization problems with different objectives. The two approaches are successfully tested at the SwissFEL injector test facility using three full-scale RF stations. The two methods are compared from both performance and complexity points of view.

Index Terms—Convex optimization, free electron laser (FEL), hierarchical control system, linear accelerator, radio frequency (RF) control, supervisory control.

I. INTRODUCTION

A LINEAR accelerator (linac) is a machine that is used to accelerate charged particles along a straight path. It is composed of a series of accelerating structures placed sequentially. Each accelerating structure module is fed by a radio frequency (RF) station, which delivers high RF power to the structures to form a sufficiently large electric field inside the cavities. An RF cavity is a metallic chamber, usually made of copper, designed with a specific geometry to make the electromagnetic waves resonate and build up an electric field inside the cavity. Since the electric field alternates with high frequency, the beam should enter the structure at precisely the right time in order to be accelerated. This can be achieved by synchronizing the beam arrival time and phase of the RF wave. The interested reader can find more details in [1] and [2].

One application of linacs is in free electron laser (FEL) machines [3]. The mechanism of an FEL machine is as follows. The electron beam is produced and injected into the linac to be accelerated to high energy. The beam then passes through the undulator, a periodic magnet array, resulting in transverse acceleration of the beam. This transverse movement causes the release of photons at a certain wavelength, depending on the electron beam energy. In summary, an FEL machine transforms the kinetic energy of a relativistic electron beam into electromagnetic radiation, in the form of high energy, short duration, and X-ray laser pulses. For more details, we refer the reader to [3].

The SwissFEL test facility machine operates in a pulsed mode with the repetition rate of 10 Hz, i.e., every 100 ms a new electron bunch is injected into the machine and accelerated. The RF is also applied in a pulsed mode with the same repetition rate as of the beam, and synchronized to the timing of the photocathode laser. The RF pulse duration is of the order of 1–3 µs, and no digital RF feedback loops run within a pulse. This implies that the beam or RF control can only be done in a run-to-run, or pulse-to-pulse, scheme, i.e., measuring the previous pulses and acting for the next pulse.

To achieve a high quality beam, it is crucial to have stable RF fields at the cavities, i.e., RF pulses with low pulse-to-pulse jitter. The pulse-to-pulse stability of the beam energy depends significantly on the pulse-to-pulse stability of the RF amplitude and phase of the stations. The RF voltage at each cavity module is controlled by its dedicated RF station control system. The local control systems are completely decoupled and work independently. The main goal of this machine is to generate electron beams with constant and identical energies. Due to disturbances, the beam energy may vary over time. These disturbances come from microphonics, i.e., mechanical vibrations, Lorentz force detuning, i.e., changes in geometry of the cavities caused by the electromagnetic field, and from some other sources [4]. Since RF voltage is not the only source of disturbances in the beam energy—other sources, such as laser timing, are also involved—it is essential to include direct beam measurements into the control framework, so that the non-RF drift sources are compensated by the RF voltage. This introduces the concept of beam-based feedback in linacs, or generally, in accelerator machines. Beam-based RF control has been studied in many laboratories [5]–[8]. These approaches are based on local PID loops with a combination of the beam information specifying the RF control set points [9], [10]. This cascaded topology works only if the outer beam-based loop runs at a lower rate than the inner RF control loop. In other words, the set points should be updated at a slower rate than the internal RF feedback loops. However, by using predictive control, the local and the supervisory RF feedback loops can run in parallel at the same rate. This has been previously studied in [11] by developing an MPC-based supervisory control. In the current contribution, we develop a supervisory control design that uses
After the electron bunch is compressed, it is accelerated multistages with successive acceleration and compression [15]. The bunch compression is done in practice, the bunch compression is done in electrons, and therefore, the electron bunch is longitudinally compressed. In practice, the bunch compression is done in electrons, and therefore, the electron bunch is longitudinally compressed. The high energy electrons catch up with the low energy electrons, and therefore, the electron bunch is longitudinally compressed. The bunch compressor is used to increase the charge density into an energy-dependent path formed by a magnetic chicane. An ultraviolet short (of the order of picoseconds) laser pulse illuminates a metallic photocathode to extract the electrons via the photo electric phenomena [13], [14]. This produces an electron bunch (a few millimeters in length), which is then accelerated by the S-band (3 GHz) RF booster to reach 450 MeV before entering the first bunch compressor chicane. The bunch compressor is used to increase the charge density by shortening the bunch length. The electron bunch is directed by shortening the bunch length. The electron bunch is directed into an energy-dependent path formed by a magnetic chicane. The high energy electrons catch up with the low energy electrons, and therefore, the electron bunch is longitudinally compressed. In practice, the bunch compression is done in multistages with successive acceleration and compression [15]. After the electron bunch is compressed, it is accelerated through the linacs to achieve the ultimate energy of 5.8 GeV with low energy spread.

The rest of this brief is organized as follows. Section II describes a single RF station system. Section III describes the control objective. In Sections IV and V, we, respectively, discuss the beam-based feedback via RF phase and amplitude distribution. Finally, Section VI concludes this brief with a comparison of the two approaches.

II. RF STATION SYSTEM

Fig. 2 illustrates a simplified RF layout of a single RF station in the SwissFEL linac. The RF C-band (5.7 GHz) signal is amplified through the preamplifier and the klystron to reach several tens of megawatts. As mentioned before, the RF signal is applied as a pulse of duration 1–3 μs. The generated high RF power is transferred through waveguides to the cavity module for beam acceleration [16]. Two RF signal measurements are measured, one at the cavity input and the other one at the cavity output, and averaged to give an estimate of the accelerating gradient over the accelerating structure. This signal has two components: RF amplitude and phase, and therefore can be represented by a vector with a certain magnitude and phase [17]. More details on the RF architecture and design are reported in [18].

III. CONTROL OBJECTIVE

The beam energy gain of station $i$, $E_i$, can be expressed as follows:

$$E_i = q v_i \cos \phi_i$$  \hspace{1cm} (1)
where $\delta E$ is the charge of the beam, and $v_i$ and $\phi_i$ are, respectively, the amplitude and phase of the RF vector at station $i$.

The total energy gain of a linac is simply the sum of all individual gains, that is

$$E = \sum_{i=1}^{N} E_i = q \sum_{i=1}^{N} v_i \cos \phi_i$$  \hspace{1cm} (2)

with $N$ denoting the number of RF stations in a linac. The phase $\phi_i$ is measured with respect to the fixed reference phase, which gives the maximum energy gain.

In the present control scheme, the RF stations operate in open loop while an optimization unit takes control over the stations. It is called a “virtual RF station”, since from the physicists’ point of view, the whole linac is usually seen as one RF station [19]. Fig. 3 schematically shows the concept of beam-based feedback through amplitude and phase distribution. The objective is to control the vector-sum magnitude and phase, or equivalently the components $v_x$ and $v_y$. In other words, given $v_x$ and $v_y$, we would like to solve the following problem for either phases, $\phi_i$’s, or amplitudes, $v_i$’s:

$$\sum_{i=1}^{N} v_i \cos \phi_i = v_x$$  \hspace{1cm} (3a)

$$\sum_{i=1}^{N} v_i \sin \phi_i = v_y.$$  \hspace{1cm} (3b)

The vector-sum phase is typically set to zero (i.e., $v_y = 0$). The beam information, and in particular the beam energy deviation, $\delta E$, is used to update $v_x$ through the following update law:

$$v_{x}^{k+1} = v_{x}^{k} + G \delta E^{k}$$  \hspace{1cm} (4)

where superscript $k$ captures the time samples (i.e., the beam pulse index), $G$ denotes a constant gain, and $\delta E^{k}$ is the energy deviation defined by

$$\delta E^{k} := E_{\text{ref}} - E^{k}$$  \hspace{1cm} (5)

where $E_{\text{ref}}$ denotes the reference energy and $E^{k}$ is the beam energy at time index $k$. This strategy is effectively equivalent to integral control of the beam energy.

At every beam pulse, the beam energy deviation is measured to update $v_x$, which is then used to solve (3) to modify the phase angles (or amplitudes). The whole calculation process should take less than 100 ms, before the next beam pulse is triggered.

We consider two approaches to the beam energy control. Manipulating the phases while keeping the amplitudes constant, and vice versa. The cross coupling between amplitude and phase in an RF station has been measured and found to be small (less than 3% variation in amplitude for a phase scan of 360°). Therefore, the coupling effect is ignored in the control design. The constant amplitude method is discussed in detail in Section IV.

### IV. BEAM-BASED FEEDBACK WITH RF PHASE DISTRIBUTION

Equation (2) relates the beam energy gain to the RF voltages. However, since we have no direct measurement of the RF amplitude inside the cavities, (2) is reformulated as

$$E = \sum_{i=1}^{N} \kappa_i \cos \phi_i$$  \hspace{1cm} (6)

where $\kappa_i$ is a constant coefficient for station $i$.

The coefficient $\kappa_i$ can be measured by changing the phase $\phi_i$ (while keeping other phases constant at zero degrees) and measuring the beam energy for several data points. That is

$$E - E_{\text{max}} = \kappa_i (1 - \cos \phi_i)$$  \hspace{1cm} (7)

where $E_{\text{max}}$ is the maximum energy gain that can be achieved by setting all phases to zero.

Fig. 4 shows a typical phase scan performed on one RF station. The coefficient $\kappa_i$ is determined by fitting a cosine function to the data.

Therefore, (3) is rewritten in the following way, using the expression for energy, given in (6), and adding the
Discrete-time index $k$:

\begin{align}
\sum_{i=1}^{N} \kappa_i \cos \phi_i^k &= E_u^k \tag{8a} \\
\sum_{i=1}^{N} \kappa_i \sin \phi_i^k &= 0 \tag{8b}
\end{align}

where subscript $u$ in $E_u^k$ is introduced to indicate that $E_u^k$ is the control input generated according to

$$E_u^k = E_{u}^{k-1} + G \delta E^k$$

with $G$ denoting a constant gain. Note that the controller, described by (9), is an integrator, introduced to remove offset in the beam energy error. Antiwindup protection is also required when the systems are operated close to their limits. The gain $G$ is empirically determined. Choosing a large gain increases the control bandwidth and speeds up the disturbance rejection but, on the other hand, it reduces the pulse-to-pulse stability margin and amplifies the noise in the loop.

To solve (8), we follow an iterative approach that linearizes the equations in (8) around predefined angles $\phi_i^*$'s, and performs the following convex optimization problem:

**Problem 1 (Phase Distribution Optimization):**

$$\min_{\delta \phi_1, \ldots, \delta \phi_N, s_x, s_y} \left( s_x - E_u^k \right)^2 + s_y^2 + \rho \left( \phi_i^* + \delta \phi_i \right)^2$$

s.t.

\begin{align}
\sum_{i=1}^{N} \kappa_i \cos \phi_i^* - \sum_{i=1}^{N} \kappa_i \cos \phi_i^* \delta \phi_i &= s_x \\
\sum_{i=1}^{N} \kappa_i \sin \phi_i^* + \sum_{i=1}^{N} \kappa_i \cos \phi_i^* \delta \phi_i &= s_y \\
|\delta \phi_i| &< 0.1, \quad i = 1, \ldots, N \\
|\phi_i^* + \delta \phi_i| &< \phi_{\max}. \tag{10}
\end{align}

To keep the linearity assumption, the optimization variables $\delta \phi_i$'s are allowed to vary within a small range (here 0.1 rad). The procedure for updating the RF phase distribution is described in Algorithm 1.

**Algorithm 1: Energy Gain Control With Phase Distribution**

1. Measure $\delta E^k$.
2. Set $\phi_i^* = 0$ for all $i = 1, \ldots, N$.
3. Solve Problem 1 to determine the optimal $\delta \phi_i$'s.
4. Update $\phi_i^* \leftarrow \phi_i^* + \delta \phi_i$, for all $i = 1, \ldots, N$.
5. If convergence is achieved,

   set $\phi_i^k = \phi_i^*$ for all $i = 1, \ldots, N$, and continue;
   otherwise

   go to step 3.
6. Apply the RF phases, $\phi_i^k$'s, to the stations.
7. Set $k = k + 1$.
8. Wait for the next beam pulse and go to step 0.

The whole iterative calculation process should take no longer than the pulse repetition time, i.e., 100 ms, to provide the angles for the next beam pulse. The convergence speed is determined by the upper bound on $|\delta \phi_i|$. Choosing small upper bound extends the convergence time, whereas allowing $\delta \phi_i$ to move in a wide range, violates the linear approximation of (3).

**A. Experimental Results**

The following experiments are conducted at the SwissFEL injector test facility with a total beam energy of 250 MeV, using a test bed linac with three full-scale RF stations. The algorithm is implemented in MATLAB, and communication with the RF stations is through a network and Experimental Physics and Industrial Control System process variables. The repetition rate of the test facility is 10 Hz, and with the help of fast optimization solvers [20], the communication is reasonably synchronous.

The maximum energy gain is initially measured by finding the “on-crest” phases, i.e., the zero phases with respect to the beam. Then, the energy gain set point, $E_{\text{ref}}$, is set to a value slightly lower than the maximum energy in order to have the RF phases in a “zig-zag” configuration, i.e., the sign of the angles alternates around zero. This gives maneuverability to the phase control to compensate the beam energy fluctuations, and to follow the energy set point.

Fig. 5 shows the experimental results of applying several step changes in the beam energy gain. Even though, in most
operations, the beam energy set point is not changed so often, the set point tracking response also demonstrates how the system behaves in case of step-like output disturbances. In this experiment, the beam energy set point is changed by 1.5 MeV with respect to the nominal energy. At time $k < 200$, the energy set point is already 1.5 MeV below the nominal energy. At $k = 400$, the set point is increased by 1.5 MeV above the operating energy. The corresponding RF phases are shown in Fig. 6. As we can see, the angles tend to zero as the energy increases. At the maximum energy, all angles are zero. In the beam-based feedback with RF phase distribution regime, the RF amplitudes are kept constant.

V. Beam-Based Feedback With RF Amplitude Distribution

In this section, we study the beam control through RF amplitudes while keeping the phases constant. For simplicity, we assume that all stations are running with “on-crest” phase, i.e., $\phi_i = 0$ for all $i = 1, \ldots, N$, and the phase is controlled locally by a phase PID loop. A similar expression to (2) can be derived in terms of RF input amplitudes. However, since the klystron drive chain is nonlinear with respect to amplitude, we can only consider small variations in amplitude

$$\delta E = \sum_{i=1}^{N} \beta_i \delta u_i$$

where $\delta u_i$ is the RF input amplitude deviation from the operating point and $\beta_i$ is a constant coefficient, analogous to $\kappa$ defined for the phase distribution in (6).

Each station might be different in regards to its contribution to the energy gain. Fig. 7 shows the energy scan for the three RF stations at the SwissFEL test facility. The klystron nonlinearity behavior can be already seen from the data points [21]. A linear model is fitted to give an estimate for $\beta_i$.

In the beam-based feedback with RF amplitude distribution, the objective is to push the klystrons close to saturation (equivalently, make $\delta u_i$’s as positive as possible) while keeping the beam energy gain constant. Operating the klystrons in saturation not only increases the power efficiency, but also reduces the pulse-to-pulse amplitude jitter coming from the preamplifier and other devices in the klystron drive chain. The following optimization problem formulates the objective:

**Problem 2 (Amplitude Distribution Optimization):**

$$\min_{\delta u_i} \sum_{i=1}^{N} \alpha_i \delta u_i$$

subject to

$$\sum_{i=1}^{N} \beta_i \delta u_i = E_u$$

and

$$u_{i_{\min}} < \tilde{u}_i + \delta u_i < u_{i_{\max}}, \quad i = 1, \ldots, N$$

where $\alpha_i$ values are nonnegative constant weights (chosen empirically), $E_u$ is the integral control input as defined in (9), and $\tilde{u}_i$ values are constant input amplitudes at the operating points of the klystrons.

During operation, the RF phases are locally controlled to be at 0°. This implies that (8b) still holds. Unlike the phase distribution approach, no iteration is needed to determine the amplitude distribution. The control scheme is described in Algorithm 2.
Fig. 10. Comparison of the beam-based feedback schemes with the open loop and local RF feedback loop results. The sampling rate is 10 Hz.

**TABLE I**

**CONTROL METHODS COMPARISON**

<table>
<thead>
<tr>
<th>Method</th>
<th>Long-term st. dev [MeV]</th>
<th>Computational complexity</th>
<th>Performance</th>
<th>Setpoint tracking speed</th>
<th>Range of setpoint</th>
<th>Influence on thermal stability of other devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization</td>
<td>0.019</td>
<td>Medium</td>
<td>Drifts compensated</td>
<td>Fast</td>
<td>Limited</td>
<td>Major</td>
</tr>
<tr>
<td>(amplitude distribution) Optimization</td>
<td>0.022</td>
<td>High</td>
<td>Drifts compensated</td>
<td>Very fast</td>
<td>Wide</td>
<td>Very minor</td>
</tr>
<tr>
<td>Local feedback loops</td>
<td>0.032</td>
<td>Low</td>
<td>With drifts</td>
<td>Slow</td>
<td>—</td>
<td>can be either minor or major</td>
</tr>
<tr>
<td>No control</td>
<td>0.038</td>
<td>—</td>
<td>With larger drifts</td>
<td>—</td>
<td>—</td>
<td>can be either minor or major</td>
</tr>
</tbody>
</table>

**Algorithm 2**: Energy Gain Control With Amplitude Distribution

1. Measure $\delta E^k$.
2. Update the control input $E^k_u = E^{k-1}_u + G\delta E^k$.
3. Update the input amplitudes $u^k_i = \bar{u}_i + \delta u_i^k$, for all $i = 1, \ldots, N$.
4. Apply the RF amplitudes, $u^k_i$'s, to the stations.
5. Set $k = k + 1$.
6. Wait for the next beam pulse and go to step 0.

**A. Experimental Results**

The experiment configuration is similar to the one described in Section V. Since the klystrons are normally operated very close to the saturation (approximately 3% below the maximum power), the RF input amplitudes can only maneuver within the limited predefined operating ranges. The RF phases are all set to zero with the local phase feedback loops running to remove phase drifts and fluctuations locally. The operating point of the klystrons, including the input amplitudes $\bar{u}_i$'s, is initially determined for a specific beam energy [22]. At the operating point, the beam-based feedback loop is closed to remove the energy variations and track small set point changes in the beam energy. For large set point changes, where all inputs would hit the upper or lower limits, the operating points of the klystrons would need to be changed.

Fig. 8 shows the closed-loop response to step changes in the beam energy set point. The beam energy is increased in three steps, from 2 MeV below the nominal energy of 200 MeV, up to 4 MeV above. Fig. 9 shows the RF input amplitude deviations for the three stations. As the beam energy increases, the amplitudes get close to the situation limits.

The way that the amplitude deviations are distributed, is determined by Problem 2.

Fig. 10 compares the two beam-based feedback methods, i.e., the RF phase and amplitude distribution, with local RF feedback case and open-loop case. In the local RF feedback regime, each station controls the RF amplitude and phase at the local cavity, i.e., without any information from the beam, using two separate PID loops for amplitude and phase control. In the open-loop case, all RF stations are operated in open loop and the beam-based feedback loop is not active. That is, local RF feedback loops are open and no beam information is used to correct the voltages. The beam energy is also influenced by non-RF sources, such as laser timing drifts. Therefore, even with stable RF amplitude and phase—so that the thermal drifts due to RF devices are compensated—some disturbance in the beam energy is expected. The two beam-based feedback algorithms remove the drifts by acting on the RF station set points. The discrepancy between performances of the amplitude and phase distribution can be explained by different gain tuning in (9). The long term relative standard deviation of the beam energy is reduced by a factor of 2, in the two beam-based approaches. With the local RF feedback loops, removing disturbances up to a bandwidth of few hertz is achievable. Thus, only slow variations and low frequency fluctuations can be addressed. The pulse-to-pulse jitter cannot be compensated via these approaches as the pulse-to-pulse noise has a stochastic behavior.

**VI. CONCLUSION AND DISCUSSION**

In this brief, we developed two control strategies to control the beam energy of a linear accelerator. In this scheme, the beam energy deviation measurement is used in the
optimization unit to distribute the individual gains over stations. In this feedback configuration, RF stations act as actuators and the controller unit is a single-input multiple-output system (see Fig. 3). The two control approaches are based on convex optimization problems that distribute the RF amplitudes and phases optimally. In the RF phase distribution method, the amplitudes are kept constant, and the beam energy is only controlled through manipulating the phases. In this method, from a given desired energy, the individual angles are determined through a constrained least-square problem (see Problem 1). The process repeats iteratively until a set of angles minimize the cost function. In the RF amplitude distribution, however, the phases are fixed at zero with local control loops, and the amplitudes are determined through a linear programming problem (see Problem 2), in which the objective is to drive the klystrons close to saturation. Both control approaches have been successfully tested at the SwissFEL injector test facility using three full-scale RF stations.

Regarding the beam control result, both methods performed similarly according to Fig. 10 and Table I. However, from implementation perspective, the phase distribution involves much more complexity, as the angles are computed through several iterations. The main advantage of the phase distribution is that the large changes in the beam energy set point are tracked much faster than the amplitude method. Changing the RF amplitudes imposes temperature fluctuations in the RF system that may take time to be stabilized. On the other hand, as already mentioned in Section V-A, the RF amplitudes are limited to vary within a predefined range. Therefore, the energy set point range is also restricted. From the experimental results, this energy range is around 5% with amplitude distribution, and at least 30% with the phase distribution method. However, achieving low beam energy with phase distribution method may not be efficient as it indicates that only a fraction of the total RF power is used to accelerate the beam.

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