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BEAM-BASED POWER DISTRIBUTION OVER MULTIPLE KLYSTRONS IN A LINEAR ACCELERATOR*

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Abstract

A linear accelerator including several klystron driver RF stations can be viewed as a single virtual RF station [1] with a certain accelerating RF voltage (in amplitude and phase). This paper develops an optimization scheme that, for a specified beam energy gain, determines the klystrons output powers and the modulators high voltages optimally. The algorithm employs the klystron nonlinear static characteristics curves to calculate the input RF amplitude of the drive chain.

INTRODUCTION

A linear accelerator (Linac) is composed of multiple Radio Frequency (RF) stations, delivering high power RF to feed the accelerating structures. If the high power is generated by klystrons, finding the appropriate operating points of the klystrons is a topic to be considered. In order to increase the RF stability as well as the efficiency, it is preferable to operate the klystron very close to its saturation limit. The saturating power depends on the high voltage of the klystron. Nonlinear characteristic curves of the klystron, make it not so straightforward to determine the high voltage and the input amplitude from a specified klystron output power. Figure 1 depicts the klystron output power versus the RF input amplitude and the voltage of the high voltage power supply (HVPS). Two contours of constant power are plotted to illustrate the problem. This issue has been previously addressed in [3] by introducing the concept of operating point determination (OPD). In this paper, we consider multiple klystrons, in which the operating points are determined according to the specified total energy gain. This leads us to the concept of beam-based multiple operating point determination (BM-OPD). In this scheme, an optimization procedure is developed which minimizes the high voltages of the klystrons, while keeping the total beam energy gain constant. Since the breakdown rate of the klystron is directly related to the high voltage level, the proposed optimization tends to reduce the probability of breakdowns. The approach is based on a convex optimization which uses the models of klystron characteristics and the energy gain of the RF stations. This method has been successfully tested at the SwissFEL injector test facility using three full-scale RF stations to simulate a Linac. The SwissFEL is currently being constructed at Paul Scherrer Institut [2]. The SwissFEL injector and the Linac RF drives operate in a pulsed mode at the rate of 100 Hz. There are 26 RF stations in the SwissFEL Linac. The proposed algorithm facilitates the RF setting with an automatic procedure for the specified energy gain of a Linac.

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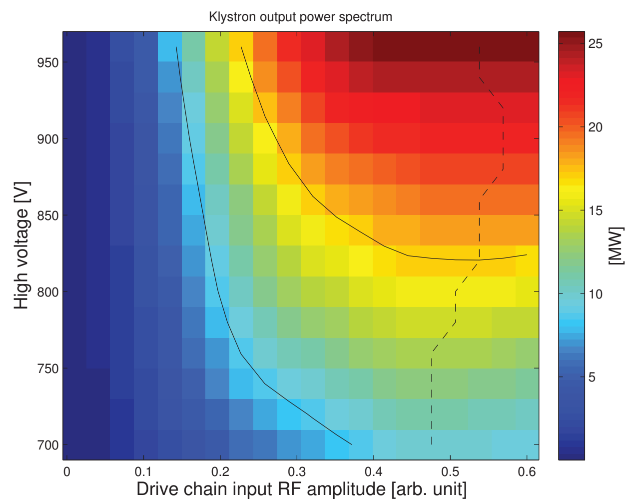

Figure 1: The klystron output power versus the RF input amplitude and the high voltage power supply setting. The curves (in black) denote the contours of constant output power. The dashed line indicates the saturating power. The klystron operating point should fall in the left side of the dashed line to avoid over-saturation.

OPTIMIZATION SCHEME

A Linac with multiple klystrons is often viewed as a single RF station with a certain energy gain. The energy gain can be tuned via each individual klystron RF amplitude as well as the high voltage. The way that the klystrons contribute to generate the desired total energy gain, is the main focus of this section. The distribution of the individual energy gain of the RF stations is done through an optimization problem. As a result, the RF power of each individual klystron is determined, which is then used as an input to the OPD, along with the predefined headroom to the saturation, to provide the assigned energy gain.

The optimization is meant to minimize the overall probability of breakdowns in klystrons, which usually occurs at higher high voltages. Throughout this study, we assume that the RF phases are set to zero, i.e. the "on-crest phase".

We consider a Linac with M klystrons. The energy gain of each RF station, ΔE_i, is related linearly to the klystron output RF amplitude. That is,

$$\Delta E_i = \alpha_i y_i + \beta_i, \quad (1)$$

where y_i denotes the output amplitude of i-th klystron , and where β_i and α_i are constants. On the other hand, according

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to the measurement, the relationship between the klystron saturating output amplitude and the high voltage is also linear:

$$\frac{y_i}{1-\eta} = \gamma_i h_i + \xi_i, \tag{2}$$

where $\frac{y_i}{1-\eta}$ is the maximum amplitude, with η representing the headroom. The h_i denotes the high voltage of the i-th klystron, and γ_i and ξ_i are some constant parameters. We denote by ΔE_{ref} to be the desired energy gain deviation of M klystrons from the nominal energy setpoint. In other words,

$$\Delta E_{\text{ref}} = E_{\text{nom}} - E_{\text{ref}}, \tag{3}$$

where E_{nom} is the nominal energy gain, or the operating point where the machine is calibrated around, and where E_{ref} is the desired total energy gain setpoint. Therefore, the summation over all individual energy gains should satisfy this constraint, i.e.,

$$\sum_{i=1}^{M} \Delta E_i = \Delta E_{\text{ref}}. \tag{4}$$

Substituting Eqs. (1) and (2) into (4), gives the following expression,

$$\sum_{i=1}^{M} \alpha_i (1-\eta)\gamma_i h_i = \Delta E_{\text{ref}} - \sum_{i=1}^{M} \alpha_i (1-\eta)\xi_i + \beta_i. \tag{5}$$

Taking $J = \sum_1^M h_i^2$ as the risk function of breakdowns, yields the following quadratic programming:

$$\begin{aligned} &\underset{h_i}{\text{minimize}} \ \sum_{i=1}^{M} h_i^2 \\ &\text{subject to} \\ &h_{i\,\text{min}} \le h_i \le h_{i\,\text{max}}, \quad i = 1, \ldots, M, \\ &\sum_{i=1}^{M} \alpha_i (1-\eta)\gamma_i h_i = \Delta E_{ref} - \sum_{i=1}^{M} (\alpha_i (1-\eta)\xi_i + \beta_i), \end{aligned} \tag{6}$$

where $h_{i\,\text{min}}$ and $h_{i\,\text{max}}$ are respectively the lower and upper bounds on the high voltages.

The optimization problem (6) reduces the rate of breakdowns which are mainly caused by large values of high voltage. It also tends to lower the total power consumption of the Linac by minimizing the high voltages[1].

EXPERIMENTAL RESULTS

In this experiment we use three full-scale RF stations, furthermore, we have $E_{\text{nom}} = 200$ MeV, $E_{\text{ref}} = 110$ MeV, and the headroom to the saturation is 5% for all klystrons. The algorithm is implemented in Matlab scripts using CVX convex optimization solver [5,6]. The communication to the machine is through network and EPICS process variables.

The optimization (6) is run for several energy setpoints E_{ref}, and the actual beam energy is measured and compared to the given setpoint. The results are plotted in Fig. 2. The error between the actual energy and the setpoint lies within 10%, which mainly comes from the model-mismatch in both klystron modeling (OPDs), and the individual energy gain parameters. Nevertheless, this error can be corrected by introducing an "offset-free" feature to the optimization problem 6. That is, the optimization is run for few iterations with the energy setpoint being updated iteratively according to

$$\Delta E_{\text{ref}}^{k+1} = \Delta E_{\text{ref}}^{k} + G\, e^k, \tag{7}$$

where superscript k denotes the time sample, G is a constant gain, and e^k is the measured energy error, i.e.,

$$e^k := E_{\text{meas.}}^k - E_{\text{ref}}, \tag{8}$$

with $E_{\text{meas.}}^k$ denoting the measured energy gain. The beam

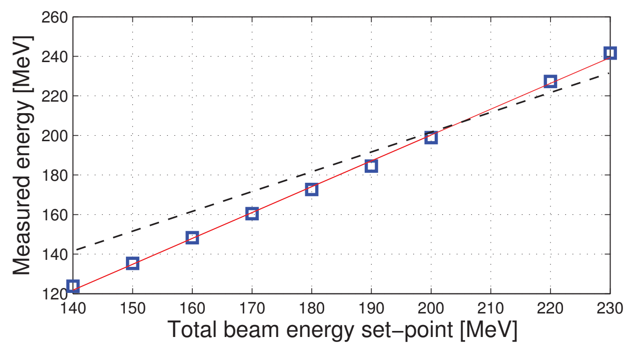

Figure 2: The total measured beam energy versus the reference (setpoint) energy. The dashed-line, which simply plots the equation $y = x$, represents the ideal open-loop response.

energy is measured at the end of the machine through the spectrometer monitor (see Fig. 3). The beam position on the x-axis gives an indication of the total energy gain. The beam spot position is adjustable by the current through the bending magnet.

Disturbance Rejection Scenario

In the following experiment, we test the behavior of the BM-OPD under disturbance situation, particularly, a breakdown of one RF station. In this case, the disturbed station fails to deliver the specified power and therefore the BM-OPD is notified, for example through the Machine Protection System, with the information of the failed station. The optimization is run with the following modified constraints on h_j and α_j,

$$\begin{aligned} h_{j\,\text{min}} = h_{j\,\text{max}} &= 0, \\ \alpha_j &= 0, \end{aligned} \tag{9}$$

where subscript j represents the failed klystron.

[1] Precisely speaking, the optimal solution to (6) does not necessarily provide the minimum power consumption. In the klystron, the quantity $\kappa = \frac{I}{V^{1.5}}$ (I: klystron current, V : Klystron voltage), known as "perveance", is normally constant [4], however, it might change with the applied voltage. Therefore, to find the minimum power consumption, one may replace the cost function by $\sum_1^M h^{2.5}$.

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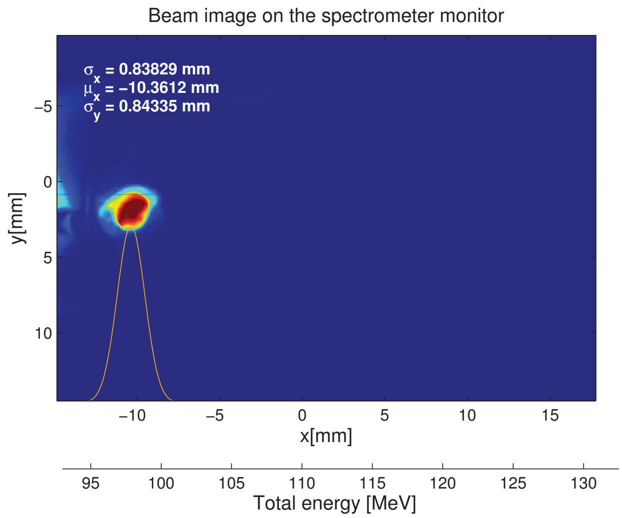

Figure 3: The electron beam image captured at the spectrometer camera. The x-position of the beam is used to estimate the beam energy.

Figure 4 illustrates the experimental results of disturbance rejection. The bending magnet current is adjusted for $E_{\mathrm{ref}} = 110$ MeV, which implies that the center of the image corresponds to E_{ref}. For this specified energy setpoint, the high voltage values are determined through the optimization (6), and the drive chain input RF amplitudes are accordingly set by the OPD. After applying the RF settings, the beam image initially falls off-center due to model-mismatch, as shown previously in Fig. 2. With a feedback from the measured beam position, according to Eq. 7, the optimization is run iteratively until the systematic error is compensated. Figure 5 plots the high voltage values of the three klystrons. The high voltages are slightly increased to correct the energy error.

At time $k = 20$, one RF station is manually set to off, which results the beam to disappear from the monitor. As stated earlier, this information is passed to the BM-OPD, and the constraints of the failed station are modified. After applying the newly calculated RF settings, the beam appears on the spectrometer monitor, however, with some error in the energy. This error is iteratively corrected and the beam is finally brought to the center at the total energy of 110 MeV. According to Fig. 5, the remaining stations tend to increase their power to compensate the energy loss.

CONCLUSION

An automatic procedure is developed which optimally set the RF input amplitude and modulator high voltage of multiple klystrons in a Linac. The main objective of the proposed method is to derive the operating points of several klystrons according to a specified total energy gain. The algorithm is also tested in case of a breakdown at one RF station. In the disturbance rejection scenario, if enough reserve power is available, the remaining stations contribute to compensate for the energy loss.

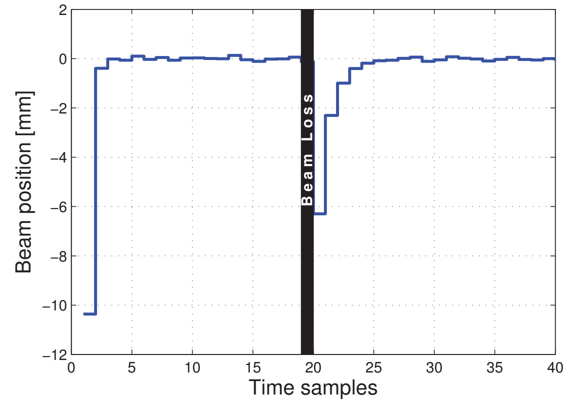

Figure 4: The beam position measured on the spectrometer monitor. The zero position corresponds to the desired energy which, in this case, is 110 MeV.

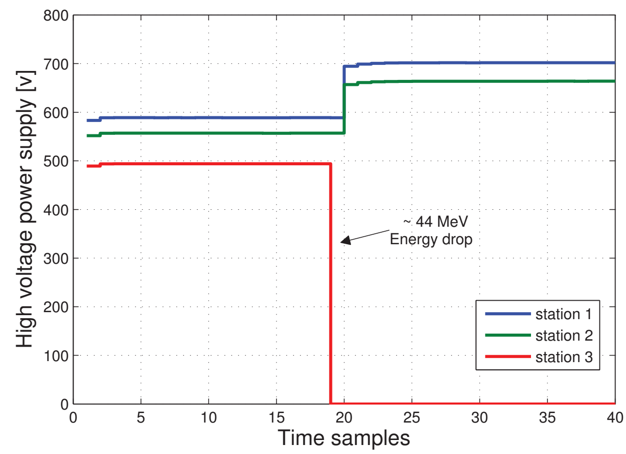

Figure 5: The high voltage value of the three klystrons at the SwissFEL injector test facility.

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