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CONF-910505--418
BNL--46643
DE92 001780

1991 Particle Accelerator Conference, San Francisco, 5/6-9/91

FEED FORWARD RF CONTROL SYSTEM OF THE ACCELERATOR TEST FACILITY

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Abstract

We report a scheme to control the amplitude and phase of the rf accelerating field in a klystron driven electron linac. The amplitude and phase distribution within the rf pulse can be controlled to follow specified functions to reduce the energy spread of the electron beam being accelerated. The scheme employs fast beam energy and phase detectors and voltage-controlled electronic attenuator and phase shifter in the amplifier chain. The control voltages of these devices are generated by arbitrary function generators. The function generators' outputs are calculated numerically using an algorithm which takes into consideration the desired target function and the deviation (due to load variations or system parameter drift) from the target function. Results of preliminary tests on producing flat rf power and phase pulses from a high power klystron indicate that amplitude variation of ±0.2% and phase variation of ±1° can be readily achieved.

Introduction

In a TW linac, the energy gain of the electron bunch in the steady state depends on the amplitude and phase of the rf field with which the bunches are accelerated. To achieve a high degree of stability of the electron beam energy and small energy spread as required by FEL and other applications, a stable high power rf source with flat-top pulses is required. With high power klystrons as rf sources, the flatness of the output amplitude and phase is dominated mainly by the high voltage pulse from the modulator, which usually has a ripple due to parasitic resonances of the stray inductance and capacitance in the PFN and in the pulse transformer. With careful design and adjustment, the modulator voltage pulse fluctuation can be kept to a small fraction of a percent as the state of the art[1-2]. However, to achieve this level of performance, it is both expensive and time-consuming. Furthermore, even with rf pulses which are perfectly flat in power and phase, the beam loading transient and beam current fluctuations induce beam energy spread in a multi-bunch operation[3]. Therefore, it is necessary to explore some other way to reduce the linac's beam energy spread.

In the following we present a scheme, whereby the klystron's rf drive signal is modulated in amplitude and phase to produce the required low energy spread, thus eliminating the need for expensive PFN adjustments. This scheme will also remove beam loading effects and drifts in other system parameters.

The modulation of the drive signal in a given rf pulse is derived from the error signals acquired during previous pulses. The reason for this is that the ATF rf pulses are about 3 μs long, a time too short to make a feed-back control system work with the given delay times in the detection as well as the control system. Thus this control system is a feed-forward scheme. The prerequisite for the success of such a scheme is a reproducibility of the pulse-to-pulse waveforms on a time scale which is longer than the response time of the control system. The ultimate performance of this system is limited only by noise, reproducibility of the modulator pulses and the accuracy of the error measurement.

Preliminary tests of this system were made on both a klystron output pulse and the fields in the ATF RF gun cavity with very encouraging results.

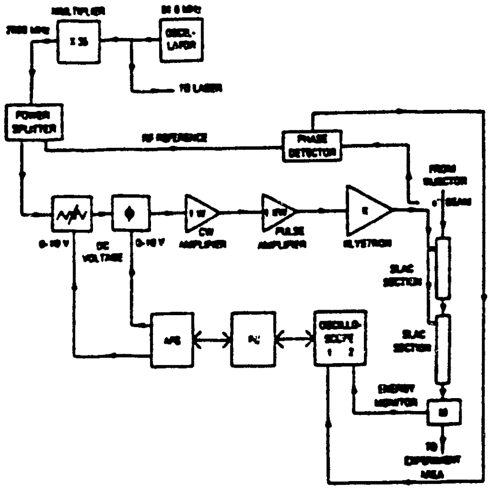

Figure 1: Schematic diagram of the feed-forward control system at ATF.

I. System Configuration

The schematic diagram of the present feed forward control system as used in the ATF is shown in Fig.1. [4] Voltage controlled fast electronic attenuator and phase shifter are installed in the drive chain of the XK-5 klystron to modulate its input. The output signal (for instance, the beam energy and rf phase) of the system are monitored with detectors read by a digital oscilloscope. The control waveforms to the attenuator and the phase-shifter are generated by the arbitrary function generators

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(AFG). The oscilloscope and the AFGs are controlled by a personal computer (PC).

The target curves are set in the computer according to system requirements. The system output signals shown on the oscilloscope are also accessible by the computer. The target function and the system output are compared in the PC. The difference signal is then used to calculate the control voltage data. The corresponding waveform corrections generated by the AFG are then applied to the attenuator and the phase-shifter.

II. Theoretical Description of the Control System

Consider a time invariant system with an input $x(t)$, and an output $y(\tau)$. Let us assume that the system is separable into a non-linear but instantaneous part represented by a function $f(x)$ and a linear part with an impulse response $g(t)$. Then one may express the output through a convolution

$$y(\tau) = \int_{-\infty}^{+\infty} f(x(t))\, g(t-\tau)\, dt \qquad (1)$$

If an increment function $\Delta x(t)$ is added to the input signal $x_0(t)$ (which may be considered as an operation level), the output of the system will be modified by the corresponding increment $\Delta y(\tau)$ around the normal operation output $y(\tau)$. If the function $f(x(t))$ is assumed to be differentiable, for a small enough $\Delta x(t)$, the relationship between the input and output increments can be expressed as:

$$\Delta y(\tau) = \int_{-\infty}^{+\infty} f^1(x_0(t))\, \Delta x(t)\, g(t-\tau)\, dt \qquad (2)$$

where $f^1(x_0)$ is the derivative of f with respect to x. By sampling the output increment $\Delta y(\tau_i)$ at times τ_i, eq.(2) can be written in a matrix form as follows:

$$\begin{pmatrix} \Delta y(\tau_1) \\ \Delta y(\tau_2) \\ \vdots \\ \Delta y(\tau_m) \end{pmatrix} = \begin{pmatrix} T_{11} & \dots & T_{1n} \\ T_{21} & \dots & T_{2n} \\ \vdots & \ddots & \vdots \\ T_{m1} & \dots & T_{mn} \end{pmatrix} \begin{pmatrix} \Delta x(t_1) \\ \Delta x(t_2) \\ \vdots \\ \Delta x(t_n) \end{pmatrix} \qquad (3)$$

where the subscripts m and n may have different values, τ_i may also be different from t_i, and $\Delta x(t_j)$ is the input increment value applied to the system at instant t_j. The matrix element T_{ij} is defined as:

$$T_{ij} = f^1(x_0(t_j))\, g(t_j - \tau_i)\Delta t \qquad (4)$$

where Δt is the sampling interval. As a result of causality, the matrix elements must satisfy the following equation:

$$T_{ij} = 0 \qquad for \quad \tau_i \le t_j \qquad (5)$$

As an approximation, the system can be assumed to be linear near $x_0(t)$. Then $f^1(x_0(t_j))$ is a constant, and we may also use causality (eq.(5)) and write eq.(3) in a very simple form:

$$\begin{pmatrix} \Delta y_1 \\ \Delta y_2 \\ \vdots \\ \Delta y_n \end{pmatrix} = \begin{pmatrix} T_1 & 0 & \dots & 0 \\ T_2 & T_1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ T_n & T_{n-1} & \dots & T_1 \end{pmatrix} \begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_n \end{pmatrix} \qquad (6)$$

where the matrix elements T_i $(i = 1,2,\dots,n)$ are constant. The T matrix elements can be obtained by measurement. This is achieved by superimposing the known deviation value, for instance, Δx_1, on the operation level $x_0(t)$, then measuring responses, Δy_i and solving Eq.(6).

In the linac system we are discussing, the input variable $x(t)$ is the control voltage applied to the attenuator (V_a) or to the phase-shifter (V_p). The non-linear function $f(x)$ is the response of the rf system, $g(t)$ is the impulse response of the beam energy to the amplitude of the rf input to the linac cavity, and Δy_i is the beam energy error from the linac output to the system requirement (target curve). By inverting the matrix T, the control voltage needed to compensate the energy error will be:

$$\Delta V_j = \frac{1}{T_1}\left[\Delta U_j - \sum_{i=1}^{j-1} T_{j-i+1}\Delta V_i\right] \qquad (7)$$

where $\Delta U_j = U_j - U_{0j}$, and U_{0j} are the target beam energy values.

Thus we have a control procedure: First the matrix T is evaluated. Then the system response is compared with the target data to obtain ΔU_j. The voltage corrections are calculated by Then the voltage corrections are applied to the attenuator to yield new values of system output U_j.

If the matrix T can represent the actual system precisely, the energy errors can be compensated by modifying the control voltage just once. With a T matrix which is a good approximation of the actual system and given an initial control voltage vector V_j which is close enough to the final value, the solution will converge fast. The required system output will be achieved after just a few applications of the correction process.

However there are a few technical problems. First, the linac system is usually nonlinear and the initial control vector V may be far from the exact solution. Furthermore, noise (both real and digital rounding error noise) results in errors in the evaluation of the matrix T. The first problem can be resolved by keeping the corrections ΔV_j small. When the accumulated correction (relative to the starting value of V_j) grows above a certain preset value, the T matrix will be re-evaluated. Thus this system will operate as an adaptive control system. The second problem can be reduced by averaging over several measurements with somewhat different applied control function deviations.

It should be pointed out that the same procedure can be applied to the rf phase control. However, for controlling both the rf phase and the beam energy (or rf amplitude) simultaneously, some measures to decouple the rf amplitude and the rf phase are needed. We have been successful in decoupling the rf amplitude and phase in the cw part of the system and still have to address the decoupling in the pulsed amplifiers.

III. Preliminary Experimental Test Results.

The rf feed forward control system has been tested on the control of the rf output of a high power S-band klystron and on the control of the field in a cavity. For this purpose, the klystron is operated in an unsaturated power level. The controllable rf pulse width is about 3 μs for the ATF. Thus, about 300 samples points, 10 ns apart are used in the system.

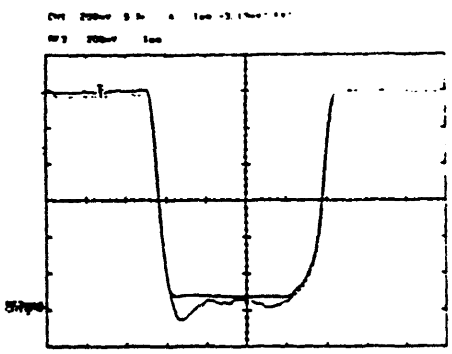

Figure 2: Comparision between uncompensated (lower curve) and compensated (upper curve) rf amplitude from the klystron output.

Fig. 2 shows the result of the klystron output control. The amplitude fluctuation before the control system is activated is about $\pm 4\%$ (lower curve). After four iterations of the control process, the power error is reduced to less than $\pm 0.2\%$ (upper curve). Fig. 3 shows the experimental results of controlling the field level of the ATF photocathode gun cavity. The amplitude variation after compensation is reduced from $\pm 5\%$ to less than $\pm 1\%$. This result is not as good as the klystron regulation test since the available rf pickup electrode in the cavity provided a very small signal and the system suffered from noise. This is not an intrinsic problem of the control method and this result is by no means the ultimate performance of the system. The cavity control system is more interesting than the klystron control, because the filling time of the cavity (about 0.8 μs) results in many non vanishing matrix elements in T.

At the time being we have not used the full automated control system in which both rf amplitude and phase are controlled simultaneously. However we have demonstrated such a process by manual control of the AFG. In this test the phase error has been reduced from $\pm 5°$ to about $\pm 0.6°$ and the amplitude error from $\pm 1.4\%$ to $\pm 0.3\%$. These experimental results, which are listed in Table I, demonstrate that amplitude fluctuation $< \pm 0.2\%$ and phase fluctuation $< 1°$ for a high power klystron output can be readily achieved.

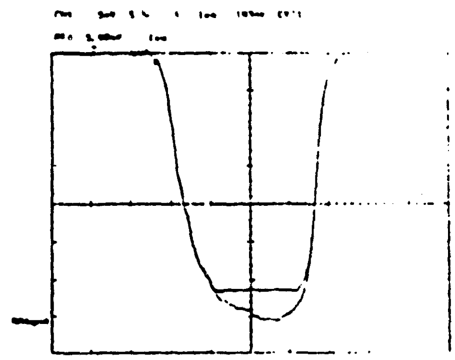

Figure 3: Comparision between uncompensated (lower curve) and compensated (upper curve) rf amplitude pulse from the rf gun cavity.

Table I. Summary of Preliminary Experiment Results

ITEMS	No Control	With Control
Klystron Power $(\pm\frac{\Delta P}{P})$	4%	0.2%
RF Cavity Power $(\pm\frac{\Delta P}{P})$	5%	1.0%
Manual Control $(\pm\frac{\Delta P}{P})$	1.4%	0.3%
Klystron $(\pm\Delta\phi)$	5°	0.6°

Note: when the klystron is operated on saturated state, the rf power fluctuation is about $\pm 0.6\%$.

In the future we would like to use this system to control the energy spread of the linac beam in ATF. For this purpose we shall use a fast-response strip-line beam position monitor in a suitable point at the post linac beam transport line, where the beam dispersion analysing power is high. The micro-pulse by micro-pulse energy of the beam will be read and this information will be used at the feed forward control system.

Acknowledgement

The authors wish to thank H. Schwartz of SLAC for providing the phase shifters and information about their application. Help from ATF members J. Sheehan and K. Batchelor has been extremely valuable. The technical support of L. De Santo and T. Monahan is also gratefully acknowledged.

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Work performed under the auspices of the U.S. Department of Energy, under contract no. DE-AC02-76CH00016.

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