A FAST FEEDBACK SYSTEM FOR CEBAF*

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A fast feedback system based on concepts of modern control theory has been implemented in the CEBAF Control System to stabilize various machine parameters. The continuous wave operation of CEBAF requires that parameters such as beam energy and position are stabilized against fast fluctuations. The beam energy must be stabilized against fast gradient and phase fluctuations in the RF accelerating system. This fast feedback system currently operates at 60 Hz rate and is integrated with EPICS. The mathematical model of the system for various feedback loops is expressed in state space formalism. The design of control law and simulation of closed-loop system response is performed using Matlab™ and Simulink™. This paper describes the process of designing control algorithms, implementation of the fast feedback system and operational experience with this system at CEBAF. The performance of this feedback system, while operating at much higher rates with high closed loop gain, can be enhanced by continually performing on-line identification of the system from the input and output data. System identification is the process of developing or improving an analytically derived mathematical representation of a physical system using experimental data. The current status of this feature is presented.

I. INTRODUCTION

The CEBAF accelerator, Figure 1, consists of 45 MeV injector, two side-by-side superconducting linacs, and 9 recirculation arcs that recirculate the beam through the linacs up to 5 times for 4 GeV total energy. Beams of different energies are separated at the first spreader and are transported through isochronous arcs to the recombiner at the entrance of the second linac. At the exit of the second linac, the beams of different energies are separated again to be sent to either Experimental Halls or through the recirculation arcs.

The beam property requirements specified for the three Experimental Halls are very stringent. The nominal value for beam emittance is specified at 20 μm < σ_x , σ_y < 50 μm in terms of r.m.s. spot size and $\sigma_{x'}$, $\sigma_{y'}$ < 100 μrad in terms of angular divergence. The stability requirement is 25% of the specified nominal value. The nominal value of average beam energy ranges between 0.5 to 4 GeV and the stability requirement range between 3×10^{-4} to 10^{-3}. The relative energy spread specification range between σ_E / E of 5×10^{-5} to 2.5×10^{-4} with a stability requirement of 25% of the nominal value. The energy spread in the emerging beam is determined by the bunch length, which is tightly controlled at CEBAF, and by the stability of the amplitude and phase of the RF fields in the superconducting cavities.

Measurement of beam position perturbations and beam energy variations have indicated [1] the presence of beam energy variations of up to 0.1% and beam position fluctuations on the order of millimeters. These disturbances are related to the first three harmonics of the AC line power. Beam instabilities of this magnitude are not acceptable through several septa in the accelerator which have beam clearances of a few millimeters. Therefore, several fast energy and orbit lock loops are needed at different locations in the accelerator to overcome these instabilities.

Efforts to identify the beam energy variations during pulsed mode operation of CEBAF have revealed [2] that there are two prominent noise components at 4 Hz and 10 Hz respectively. A prototype fast energy lock system based on concepts of modern control theory was built and successfully tested [2] for validity of the concept and the proposed scheme of implementation in existing control system hardware and software.

II. ARCHITECTURE OF THE SYSTEM

Figure 1 provides an overview of the type and location of the fast feedback loops (locks) that have been planned for this year. A fast energy lock loop stabilizes the energy of the beam at a particular location in the accelerator against beam energy variations caused by effects such as phase and gradient fluctuations in RF cavities. The beam energy variations for a particular lock are determined from 5 beam position monitors (BPM) installed in dispersive regions in the vicinity of the lock location. The corrective action against energy variations is made by modulating the accelerating voltage in the RF vernier cavities upstream of the lock location. The control hardware for the energy lock BPMs and the corrector cavities is located in two separate buildings, Figure 2, and is therefore controlled by two different I/O controllers (IOC-Motorola

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68040) which are linked by Ethernet. The action of a fast feedback loop can be classified into three tasks: measurement, computation of correction signal, and actuation. In the case of energy lock loops, the tasks of measurement and computation take place on one measurement IOC and actuation takes place on a different IOC that controls RF hardware.

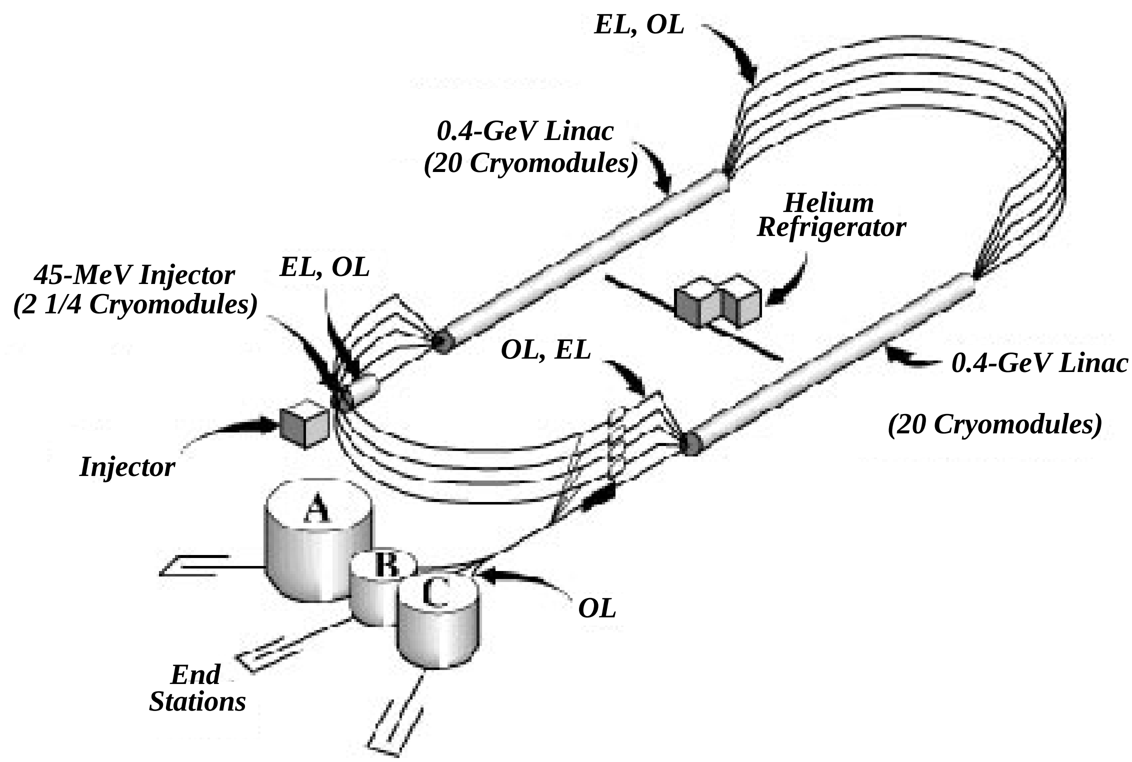

Figure 1: Schematic Diagram with Fast Lock Locations. EL - Energy Lock, OL - Orbit Lock

BPM data is obtained directly from low level data acquisition software. The control input signal is calculated using the BPM measurements of the current sample instant and the predicted state of the system at the same sample instant. This correction signal is sent over Ethernet to the RF IOC which, through a VME DAC resident in same crate, sends a 5 V signal to the analog offset input on the RF control module hardware.

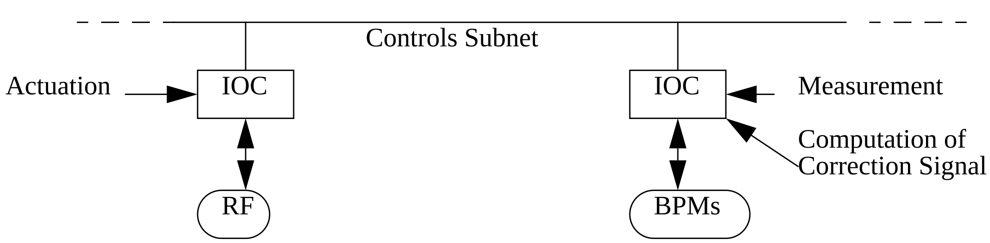

Figure 2: Schematic Layout Fast Energy Lock

The fast orbit lock system controls the beam orbit (position and angle) with respect to a desired reference orbit at a particular location in the accelerator. As in the case of the energy locks, the orbit lock uses measurements from 5 BPMs to determine the orbit. The magnetic field in 2 horizontal and 2 vertical correctors upstream of the lock location is modulated to correct for fluctuations in beam position and angle. Unlike the energy lock, all the three tasks of measurement, computation of correction signal and actuation take place on the same IOC. Custom-built air-cored correctors that can produce the desired amount of bending field for a particular orbit lock location (e.g. 750 gauss-cm for East arc orbit lock) will be used as actuators for the fast orbit locks. These fast correctors will be powered by a modified version of a standard CEBAF trim card. The modified trim card accepts an 2.5 V analog correction signal generated by a VME DAC. The frequency response of the modified trim card system connected to a fast corrector is approximately 1.2 kHz.

Presently developed orbit and energy locks will operate at a 60 Hz rate, which is the frequency of the beam synchronization pulse. The currently available low-level data acquisition software for the BPMs can provide position signals at a maximum rate of 60 Hz, which limits the rate at which the feedback loops can operate. There are plans to streamline and upgrade the low-level data acquisition software for some of the BPMs so that they can provide beam position updates in the vicinity of 1kHz rate. In order to run the energy lock loops at higher rates, a reflective memory network will have to be set up between the measurement IOCs and the RF IOCs, since Ethernet cannot be used as a reliable means of communicating the correction signal to RF IOCs at rates greater than 240 Hz.

The feedback loop software is divided in two parts: EPICS [3] software and VxWorks [4] software. EPICS software manages the Graphical User Interface (GUI) for the feedback loop, triggers the appropriate modules of VxWorks software as required and monitors the status of the loop. The tasks of measurement, computation of correction signal and actuation are done using VxWorks software. The timing for this software is synchronized from the beam synchronization pulse signal. Figure 3 shows a schematic diagram of the software layout for an energy lock loop. The organization of the VxWorks software is described in reference [2].

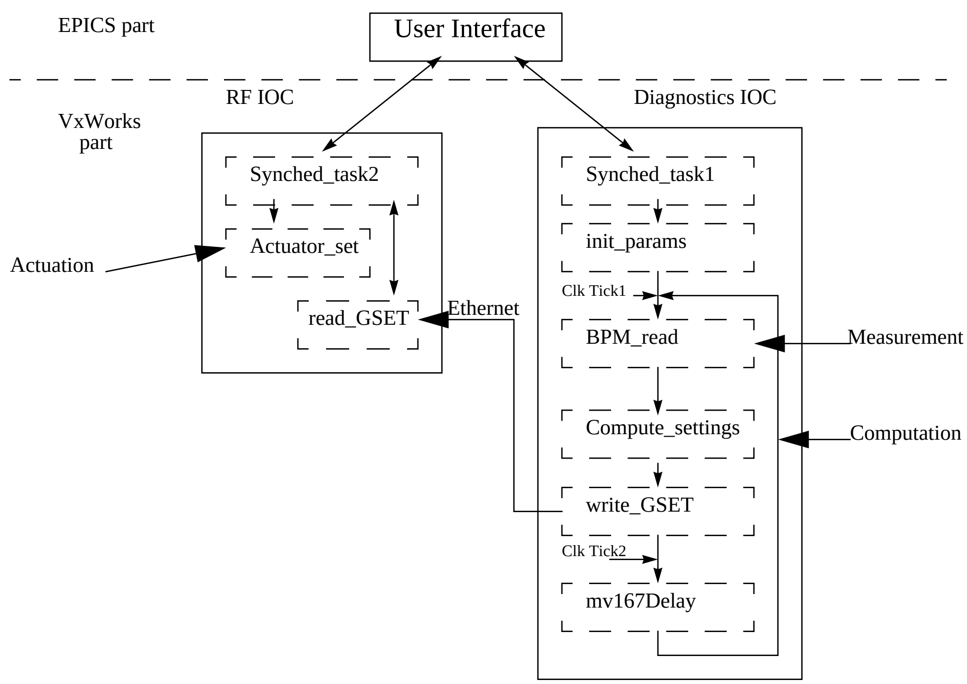

Figure 3: Schematic Software Layout for Energy Lock Loop

III. MODELLING OF SYSTEM

The objective of using fast energy and orbit locks is to lock the beam energy and beam orbit at a desired location in the accelerator. Thus, the quantities of interest at the desired lock location are $[X, X', Y, Y', \Delta E / E]$, namely the position and angle of trajectory of beam in X and Y planes and the energy variation. The variations in these quantities need to be estimated from BPM measurements in the presence of sensor noise and a corrective action needs to be taken using actuators such as corrector magnets and RF vernier cavities in the presence of process noise. Thus, modelling of the system in the state space formalism of digital control theory [5] and design of an optimal state estimator which estimates $[X, X', Y, Y', \Delta E / E]$ and an optimal controller provide a suitable solution. The description of the system in state space formalism is given by

$$x(k+1) = Ax(k) + Bu(k) + w(k) \tag{1}$$

$$y(k) = Cx(k) + Du(k) + v(k) \tag{2}$$

x(k) is the state vector which contains the attributes of the system that are dynamically significant, *A* is the system dynamic matrix which takes system states from sample instant k to $k+1$, B is the control input matrix which takes the control inputs to the state vector, $u(k)$ is the vector of control inputs to the system, $w(k)$ is the process noise vector. $y(k)$ is the vector of measurements, C is the measurement matrix which takes the measurements to states, $v(k)$ is the measurement noise vector. The state vector is $x = [X_o, X'_o, Y_o, Y_o', \Delta E/E]$. The C matrix contains the transfer matrix terms $R_{11}, R_{12}, R_{33}, R_{34}, R_{16}$ for the BPMs from a reference point.

A Kalman filter is used to estimate the states from the BPM measurements. The measurement update from sample instant k is obtained using

$$\hat{x}(k) = \bar{x}(k) + L(y(k) - C\bar{x}(k) - Du(k)) \tag{3}$$

and the time update that takes the state vector from sample instant k to $k+1$ is obtained using

$$\bar{x}(k+1) = A\hat{x}(k) + Bu(k) \tag{4}$$

Here $\hat{x}(k)$ is the estimated state vector and $\bar{x}(k+1)$ is the predicted state vector for sample instant $k+1$ obtained from the estimated state at time instant k. The controller equations that are used for the feedback loop can be obtained by combining the above two equations and are described as

$$\bar{x}(k+1) = A\bar{x}(k) + Bu(k) + AL(y(k) - C\bar{x}(k) - Du(k)) \tag{5}$$

$$u(k) = -K \cdot \hat{x}(k) \tag{6}$$

L is the state estimator gain matrix and K is the controller gain matrix. The equation 5 is used to estimate the state vector at next sample instant $k+1$. This equation contains three terms. The first term uses the system dynamic matrix A and the state vector at time k and calculates the new state. The second term which uses the control input matrix B and puts in the effect of actuator settings on the state. The third term is the correction term between estimated and actual states obtained from the measurements. Equation 6 is used to calculate the actuator setting based on the current state estimate using negative state feedback through an optimal gain matrix K.

Matrices A, B, C, D, K and L that are used to compute control input $u(k)$ can be calculated from the analytically obtained model of the relevant subsystem of the accelerator and an estimate of process and sensor noises. These matrices can also be extracted from experimentally collected pulsed response input/output data for a given set of BPMs and actuators for a particular lock using the ERA system identification algorithm [6]. Satisfactory response of controller and estimator is verified by performing simulations of the closed loop system using Simulink™. If the response of controller and estimator for system performance specification is found satisfactory, then the identified matrices are stored in a file which is read at the time of feedback loop initialization.

IV. EXTRACTION OF THE SYSTEM MODEL USING SYSTEM IDENTIFICATION

The advantages of using an identified system model and estimator gain matrices in calculating the control input for a feedback loop are described by following two arguments. Firstly, an analytically derived model for a feedback loop may not accurately represent the actual hardware in the accelerator. Secondly, a Kalman filter is used as a state estimator for both orbit and energy lock systems; one of its well known disadvantages is that it can neither adjust itself to track a changing environment, nor can it correct the error caused by incorrect assumptions of measurement and process noise covariances that are used to design it. Thus, if the system matrices, along with the estimator and the controller gain matrices that are used by a feedback loop, are constantly updated to reflect the actual system environment, then the performance of the feedback system can be substantially improved. Currently available system identification algorithms cannot be used for on-line implementation and a suitable algorithm is being developed.

The scheme of obtaining a system model using system identification was tested for the injector energy lock. The first step in this process was to collect pulse response input/output data for a given set of BPMs and RF vernier cavities. The accelerating gradient in the vernier cavities was modulated with a sinusoidal wave with different sets of frequencies and amplitudes and corresponding BPM measurements were recorded along with the modulation signal. Pulse response data for each set of modulation (fixed frequency and amplitude) was processed through the system identification toolbox SOCIT [7] to obtain the system matrices for the feedback loop.

The algorithm used for system identification is known as Eigensystem Realization Algorithm (ERA) which is discussed in detail in references [6] and [8]. The basic scheme of system realization from the experimental input/output data is described here. Consider a system characterized in state space formalism as

$$x(k+1) = Ax(k) + Bu(k) \quad (7)$$

$$y(k) = Cx(k) + Du(k) \quad (8)$$

If an input described by $u_i(k) = 1$ for (i = 1,2, .., r) and $u_i(k) = 0$ for (k=1, 2, 3, ...) is substituted in equations 8 and 9 and results are assembled into a pulse response matrix with dimensions *m* x *r* (where r = number of inputs, m = number of outputs) then we get

$Y_o = D, Y_1 = CB, Y_2 = CAB, \ldots , Y_k = CA^{k-1}B$

These matrices in sequence are known as Markov parameters. System realization begins by forming a generalized $\alpha m \times \beta r$ Hankel matrix from measured Markov parameters.

$$H(k-1) = \begin{bmatrix} Y_k & Y_{k+1} & \ldots & Y_{k+\beta-1} \\ Y_{k+1} & Y_{k+2} & \ldots & Y_{k+\beta} \\ \ldots & \ldots & \ldots & \ldots \\ Y_{k+\alpha-1} & Y_{k+\alpha} & \ldots & Y_{k+\alpha+\beta-2} \end{bmatrix} \quad (9)$$

The singular value decomposition [9] of the above matrix for k =1 is given by

$$H(0) = R \cdot \Sigma \cdot S^T \quad (10)$$

Now, the system matrices A, B, C can be obtained from the above equation as

$$B = \Sigma^{1/2} \cdot S^T \cdot E_r \quad (11)$$

$$C = E_m \cdot R \cdot \Sigma^{1/2} \quad (12)$$

$$A = \Sigma^{-1/2} \cdot R^T \cdot H(1) \cdot S \cdot \Sigma^{-1/2} \quad (13)$$

where E_m and E_r are matrices of ones and zeros with dimensions *m* and *r* used to filter *B* and *C* matrices from *R* and *S*.

V. RESULTS AND CONCLUSIONS

The injector energy lock has been tested successfully. One of the requirements on the state estimator for this system is that the estimator should be able to distinguish between position changes caused by energy variations and that caused by betatron oscillations.

Figure 4 shows a screen of the injector energy lock user interface displaying the effect of closing the loop on the states *X, X´,* $\Delta E/E$. An energy change of 0.225 MeV was introduced upstream of the lock location while the energy lock loop was operating in “Compute mode” (i.e. actuators were disabled). Figure 4 indicates that the state estimator accurately shows the energy change that was introduced and when the loop was closed (i.e. actuators enabled) the energy error was corrected. During the commissioning stage of the injector energy lock loop a series of open loop tests were performed to study the estimator response to position and energy changes upstream of the lock location. The results of these tests indicate a satisfactory response by the state estimator.

The injector energy lock loop has been operated for several 6-7 hour periods without user intervention. The closed loop system characteristics (Bode plot) are currently being studied.

The injector energy lock was operated using the system matrices that were obtained by processing pulsed response data using the ERA system identification algorithm. A marked improvement in closed loop system performance has been observed when the energy lock was run using identified system matrices.

Currently the fast feedback software is being replicated for the installation of fast locks at various locations in the accelerator. A set of orbit and energy lock loops at the end of first linac will be commissioned in a couple of weeks. Work is currently under progress to develop an on-line system identification mechanism that will continually observe (at a slower rate compared with the operating rate of the feedback loop) the feedback loop input/output data and update the system matrices used by feedback loops in order to enhance their closed loop performance.

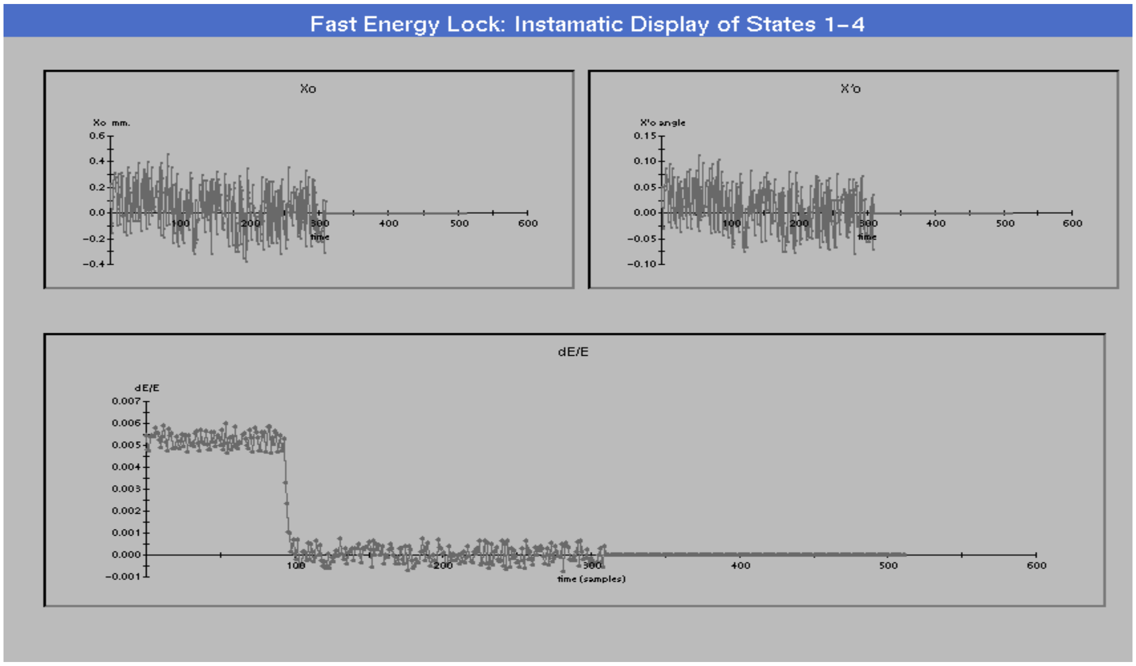

Figure 4: Injector Energy Lock - Effect of closing the loop on *X, X´*, $\Delta E/E$

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