

MATLAB Scripts for RF Commissioning at the LANSCCE LINAC

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O. Overview

In LANSCCE LINAC is composed of one 201.25 MHz Drift-Tube_Linac (DTL) sector and seven 805MHz Coupled-Cavity Linac(CCL) sectors. A 805MHz sector is composed of 6~7 CCLs with one high voltage system, Capacity Bank. In contrast, the 201MHz sector is composed 4 DTLs and each DTL has its own high voltage system. The LLRF system of 201MHz DTL sector was digitized and four of 805 MHz CCL sectors were digitized in last several years. Because of the digitization accompanied with the LANSCCE Control System(LCS) network, the network based control of LLRF system became possible. Control parameters of LLRF system are assigned with parameter variables(PVs) of the EPICS Database and the operation of the (LL)RF system can be performed by adjusting those PVs properly. MATLAB is used widely in LANSCCE for signal/image analysis and synthesis of LLRF digital signal processing(DSP). MATLAB is also used for controlling PVs of (LL)RF system. For this, MATLAB version of EPICS channel access(CA) was developed, where MATLAB m-script uses OS function "system" to call CA functions, *caget*, *caput*, etc..

The procedure of the RF operation and Beam operation is comprised of (I) turn on RF and adjust amplitude and phase set points of the cavity field to the pre-assigned target values; (II) calibrate the open loop gain and phase; (III) close the PI feedback loop and calibrate the cavity amplitude and the cavity phase of the external measurements of them to the stored target values; (IV) tune the beam feedforward controller.

Automations of (I), (III), (IV) are accompanied with callings of MATLAB functions.

I. RF TURN ON for Start Up or VSWR Recovery

RF turn on and adjustments of amplitude and phase set points are performed either for the first start up of the LINAC RF operation or for the RF Trip Recovery. Target amplitude and phase set points are retrieved from an autosaved data file. The amplitude set point increment rate is pre-assigned. While the amplitude set point is increased, the reflected power and the klystron power are monitored to prevent VSWR(RF trip). The reflected power threshold is pre-assigned from the operational experience. When the amplitude set point is increased, the monitored reflected power may be over the threshold. In that case, the amplitude set point increment rate is adjusted by applying a fuzzy logic.

This procedure is coded in a MATLAB function(*olpstartup.m*) and can be performed for one Module at a time or for part or all modules in a sector. (Example below shows simultaneous startups of 3 Modules in a 805MHz sector). The call to the MATLAB function for the startup is implemented on EPICS EDM screen (Figure 2) with Shell Command of Controls Library.

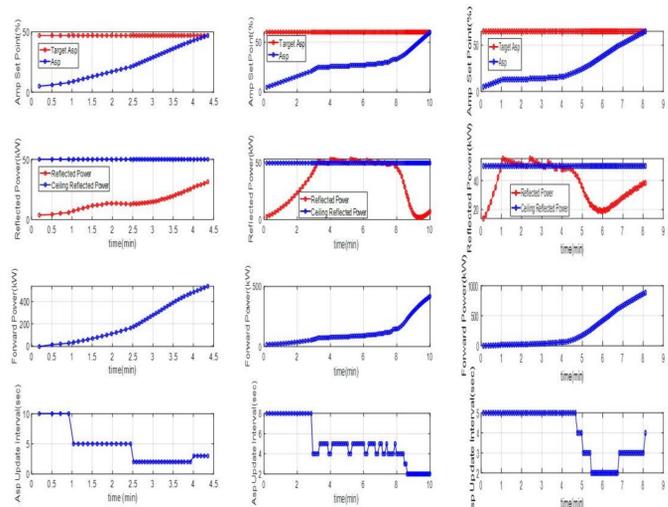


Figure 1. PV trajectories while RF turn on procedure for 3 Modules are performed simultaneously. (Left Col.: M6, middle col.: M7, right col.: M8)

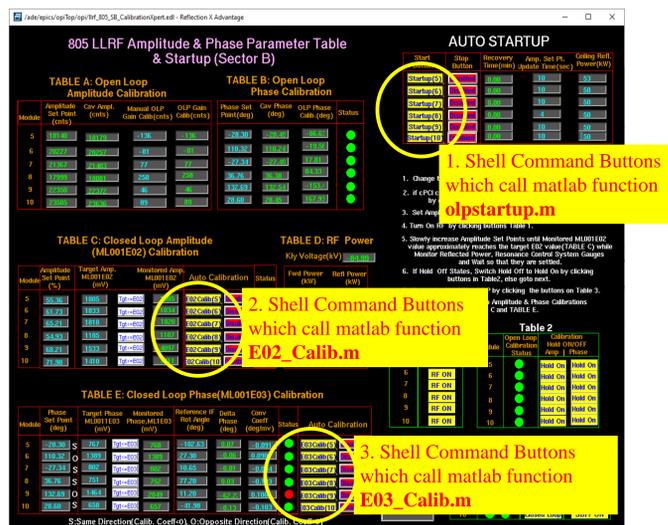


Figure 2. LLRF System Status Monitoring EDM Screen

Abstract

The linear accelerator (LINAC) at the Los Alamos Neutron Science Center (LANSCCE) consists of Pre-buncher, Main-Buncher, low-energy beam transport (LEBT), four 201.25-MHz Drift Tube Linacs (DTLs) and forty-four 805-MHz Coupled Cavity Linacs(CCLs). As a part of the upcoming LANSCCE Modernization project, low-level RF (LLRF) systems of four 201-MHz DTLs and twenty-six 805-MHz SCLs are digitized. Hence the network-based control of the cavity field and RF commissioning are possible. Each LLRF and high-power RF (HPRF) systems have many process variables (PVs) located on different computer control screens provided by the Extensible Display Manager (EDM). Several MATLAB m-scripts have been developed to efficiently process the necessary PVs while auto-start, amplitude/phase calibration, gain tuning of the cavity field feedback controllers, gain and phase tuning of the beam feedforward controllers, and high power RF trip recovery, processes are configured and validated. This paper addresses the sequence of RF commissioning of the LANSCCE LINAC from the time of RF-turn-on to beam feedforward control and its relevant EDMs and MATLAB m-scripts.

II. OPEN LOOP CALIBRATION-DECOUPLING I/Q CHANNEL CROSS TALKING

The Cavity Field Control System in I/Q Domain is a Two-Input Two-Output(TITO) System and there exist crosstalks between I/ Q channels. A signal based dynamical decoupling controller removes the crosstalks. The decoupling controller is implemented on field control system's FPGA with MATLAB Simulink/DSP Builder of Intel and the sampled controller parameters are displayed on EDM screen(Figure3).

$$W(s) = \frac{A_r^{FT}}{A_{y0}^{FT}} \begin{bmatrix} \cos(\theta_r^{FT} - \theta_{y0}^{FT}) & -\sin(\theta_r^{FT} - \theta_{y0}^{FT}) \\ \sin(\theta_r^{FT} - \theta_{y0}^{FT}) & \cos(\theta_r^{FT} - \theta_{y0}^{FT}) \end{bmatrix}$$

A_r^{FT}, θ_r^{FT} : Amplitude/Phase Set Points at the RF flat top
 $A_{y0}^{FT}, \theta_{y0}^{FT}$: Raw Amplitude/Phase at the LLRF Control system at the RF flat top

$$G_p(s) = \frac{1}{T_p s + 1} (I + \Delta(s, \Delta\omega)), \quad \|\Delta(j\omega, \Delta\omega)\|_{\infty} < 1$$

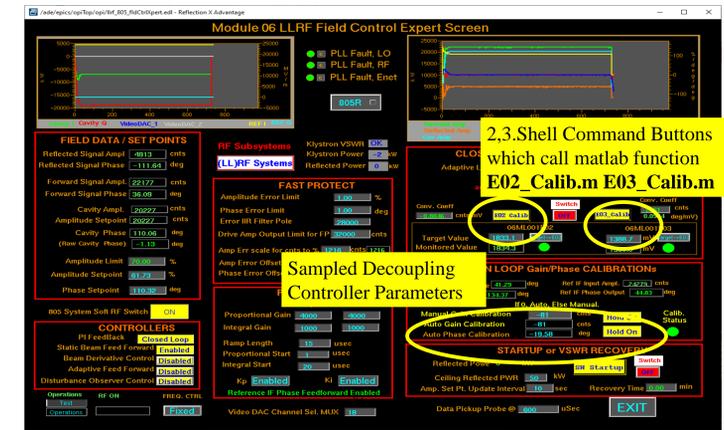


Figure 3. Field Control EDM Screen

III. PI Feedback Controller and Closed Loop Calibration

Discrete Time PI Controller

$$C_D(z) = \frac{K_P}{2^{13}} + \frac{K_I}{2^{15}} \frac{1}{1-z^{-1}}$$

Closed Loop Calibration:

In LANSCCE LLRF system, independent, external instruments(AD5511 RF Envelope Detector, AD8302 RF Phase Detector) are deployed to measure the cavity field amplitude and cavity field phase from cavity RF signal with respect to the 201.25MHz, 805MHz reference RF. The reference values of them (target values) are obtained during the beam tuning. These independent amplitude and phase values are used valuably when the operating points of the LLRF, high power RF subsystems, resonance control/water cooling systems, and other systems of LINAC are changed. The calls of the MATLAB functions (*E02_Calib.m*, *E03_Calib.m*) for the gain and phase calibrations are implemented on EPICS EDM screen (Figure 2 or Figure 3) with Shell Command of Controls Library.

Feedforward Controller Tuning:

Two Tuning Algorithms are implemented with MATLAB functions (*sbffgrid.m* for the grid search tuning and *sbffgradsearch.m* for the iterative gradient search tuning). *sbffgrid.m* can be run standalone iteratively with finer grids or run as a parameter initialization process of the *sbffgradsearch.m*. A batch m-script(*bfftune.bat.m*) implements the menu that multiplexes function call to *sbffgrid.m*, *sbffgradsearch.m*. The call to the MATLAB functions is implemented on EPICS EDM screen (Figure 4) with Shell Command of Controls Library.

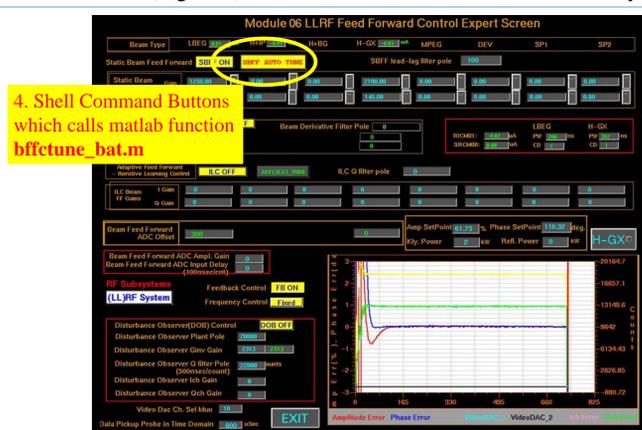


Figure 4. Feedforward Control EDM Screen

IV. BEAM FEEDFORWARD CONTROLLER TUNING

Grid Search Based Feedforward Controller Tuning:

At a given beam current, the optimal controller gain and phase are searched on the discrete grids on the gain/phase to minimize the performance index:

Phase grid $\vec{\rho}_\theta = [\theta_L: \Delta\theta: \theta_H] = [\theta(0), \theta(1), \theta(2), \dots, \theta(M)]$

Errors used for the Definition of the Cost Function $e_A(t), e_\theta(t)$ amplitude, phase errors

Controller Gain Vector $\rho = [\rho_A \ \rho_\theta]^T$

Performance Index $\vec{J}_p = [J_g(0), J_g(1), \dots, J_g(M)]$
 $J_g(i) = \max(\|e_A\|_{\infty}, \|e_\theta\|_{\infty})$ i: grid index

Phase Grid Update Law $\theta_L(j+1) = \rho_\theta^*(j) - \Delta\theta(j)$, $\theta_H(j+1) = \rho_\theta^*(j) + \Delta\theta(j)$, $\Delta\theta(j+1) = \frac{\Delta\theta(j)}{2}$ j: trial number

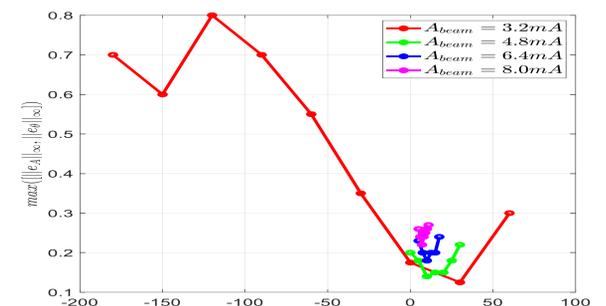


Figure 5. Four Trial results of Phase Grid Search. As the beam current is increased, the phase grid becomes finer and for each beam current, the optimal controller phase found, $\rho_\theta^* = [30, 10, 10, 7]$ degrees. $\rho_A^* = 2500$ for all trials

Fine Tuning of the Beam Feedforward Controller using DOB estimates complex beam current:

At full strength beam current, controller parameters ρ_I, ρ_Q in I/Q coordinate are searched by applying the Gradient Search iteratively.

Beam Feedforward Controller $u_{FF} t = \frac{\rho_I d_I(t)}{\rho_Q d_Q(t)}$, $d_I(t), d_Q(t)$: Estimated I/Q components of Beam by DOB

Errors used for the Definition of the Cost Function $e_I(t) = I_{sp}(t) - I_{cav}(t)$, $e_Q(t) = Q_{sp}(t) - Q_{cav}(t)$ I/Q components of the cavity field error

Controller Gain Vector $\rho = [\rho_I \ \rho_Q]^T$

Cost Function $J(\rho) = \frac{1}{2N} \sum_{i=1}^N (e_I^2(i) + e_Q^2(i))$ N: samples of collected data

Gain Update Law $\rho^{(k+1)} = \rho^{(k)} - \alpha \nabla J(\rho^{(k)})$ k: Iteration number

Jacobian $\nabla J(\rho^{(k)}) = \begin{bmatrix} -\frac{1}{N} \sum_{i=1}^N e_I(i) \frac{\partial y_I(i)}{\partial \rho_I} \hat{d}_I(i), \\ -\frac{1}{N} \sum_{i=1}^N e_Q(i) \frac{\partial y_Q(i)}{\partial \rho_Q} \hat{d}_Q(i) \end{bmatrix}$

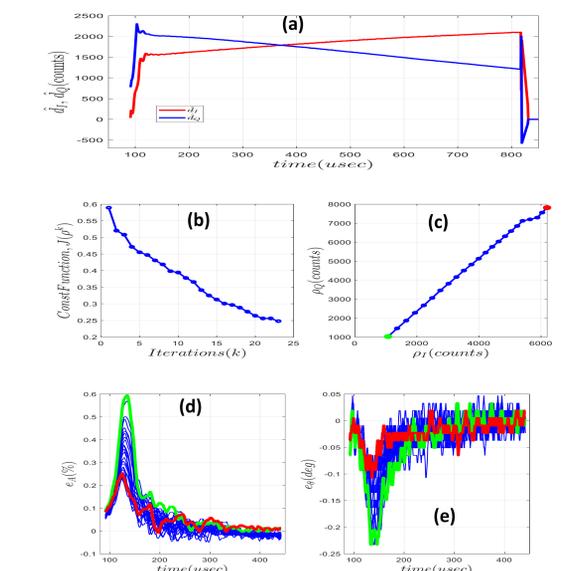


Figure 6. Performance results of the Iterative Tuning method: (a) Complex beam current estimates; (b) Cost function; (c) Controller parameters; (d) Amplitude error; and (e) Phase error. Green: Initial values, Red: Final Values.