Beam loading Compensation of LANSCE Digital Low Level Radio Frequency System

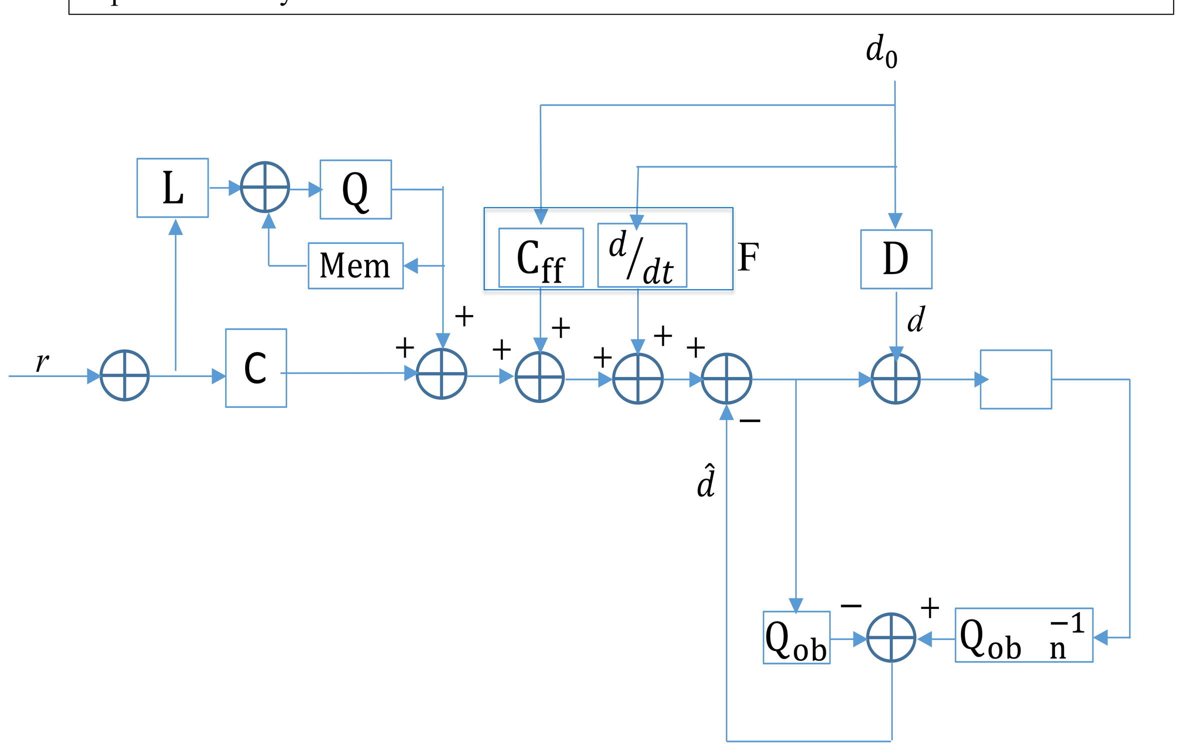
Sungil Kwon, L. Castellano, M. Prokop, P. Torrez, D. Rees, A. Scheinker, and P. Van Rooy
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Abstract

The Los Alamos Neutron Science Center (LANSCE) proton accelerator supports multiple experimental areas and accelerates several beam species, each having its own peak current value, repetition rate, and chopping characteristics. A new digital low-level RF system (LLRF) was designed and deployed on 201MHz drift-tube-linac 805MHz side-coupled-cavity linac section of LANSCE. This new system is part of a modernization of the existing analog cavity-field controls that were originally developed and put into service forty-five years ago. For stabilization of the cavity field amplitude and phase during beam loading, a proportional-integral feedback controller has been implemented. For the multi-beam loading compensation, a static beam feedforward controller, a disturbance observer based controller, a disturbance derivative controller, and an iterative learning controller have been implemented in parallel. In this paper, the controller's architectures are described, and the performances of the controllers is presented.

I. Overall Control System Block Diagram

LLRF Control System Block Diagram. PI feedback Controller, C(s), Iterative Learning Controller(ILC), Beam Feedforward Controller(BFFC), and Disturbance Observer(DOB) based Controller are implemented. PI feedback Controller and BFFC are the default controllers, ILC and DOB based Controllers are enhancements. d_0 is the detected beam working as if it is the extraneous disturbance. Note that ILC uses the overall control output but not ILC output for the update of the controller output. This ILC structure improves stability robustness.



II. PI Feedback Control

Discrete Time PI Controller (16 bit signed integer format implementation on FPGA) :

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

Continuous Time PI Controller :

$$C(s) = \left(\frac{K_P}{2^{13}} + \frac{K_I}{2^{15}}\right) + \frac{K_I}{2^{15}\cdot t_s}\frac{1}{s}$$

t_s : Sampling time

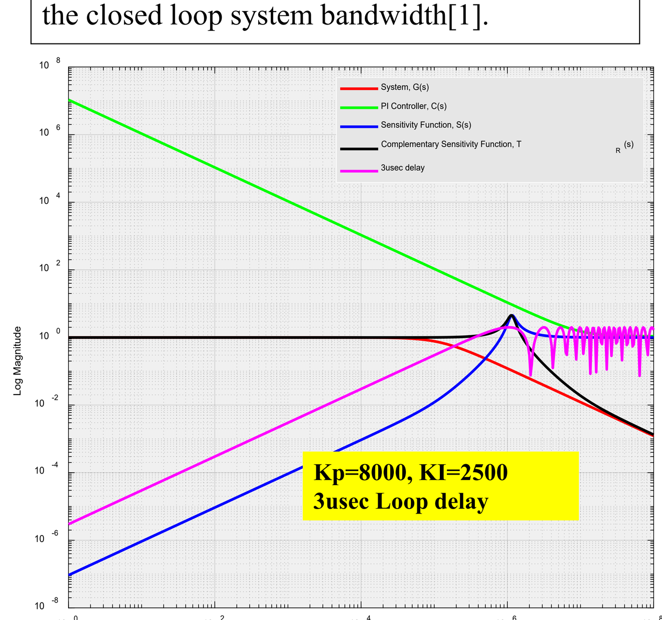
Output Response: $Y(s) = T_R(s)R(s) + S(s)G(s)D(s)$

Error Response: $E(s) = -S(s)R(s) + S(s)D(s)$

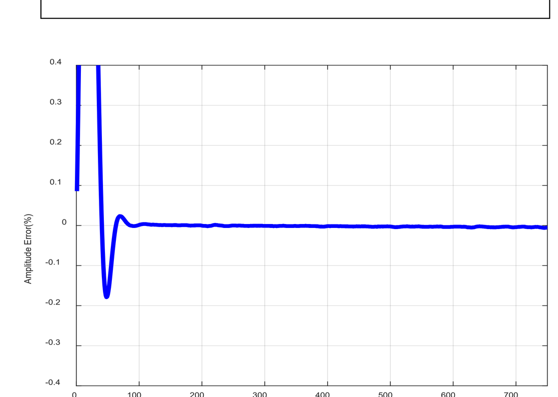
Complementary Sensitivity Function: $T_R(s) = \dfrac{GC}{1+GC}$

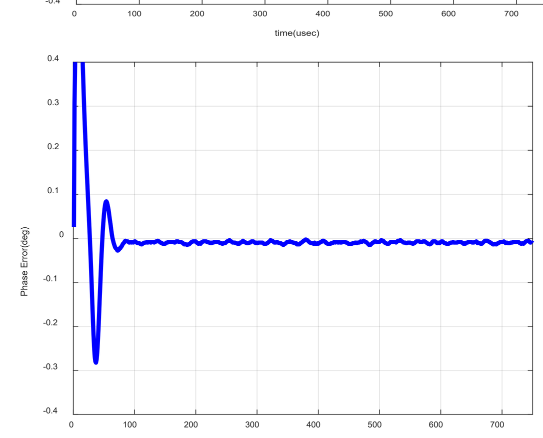
Sensitivity Function: $S(s) = \dfrac{1}{1+GC}$

Frequency Domain Responses of the Feedback Control System: The 3db bandwidth of the side-coupled-linac cavity is 19.5kHz and the closed loop system's bandwidth is 287kHz(time constant: 0.56usec), resulting in much smaller response time. The peak magnitude of S(*jw*) is 11 at 183kHz. This means that the disturbance D(*jw*) at this frequency is amplified with the gain of 11. Magnitude of S(*jw*) and magnitude of delay meet at 151kHz and the magnitude of S(*jw*) at that frequency is 5. When the KI value increases further and the peak magnitude of S(*jw*) is in the region where the delay magnitude is ringing, then the closed loop cavity field will oscillating. The peak magnitude of S(*jw*) can be reduced to the recommended value 1.5~2 with the sacrifice of the closed loop system bandwidth[1].



Time Domain Response of the Feedback Control System without beam: The amplitude set point and phase set point have 30usec ramp time to reach the flattop set point values. The set point ramp is introduced to reduce the reflected power in the field transient period. The ramp time is programmable. Note that the beam is loaded at 95usec and beam gate pulse length is 625usec.

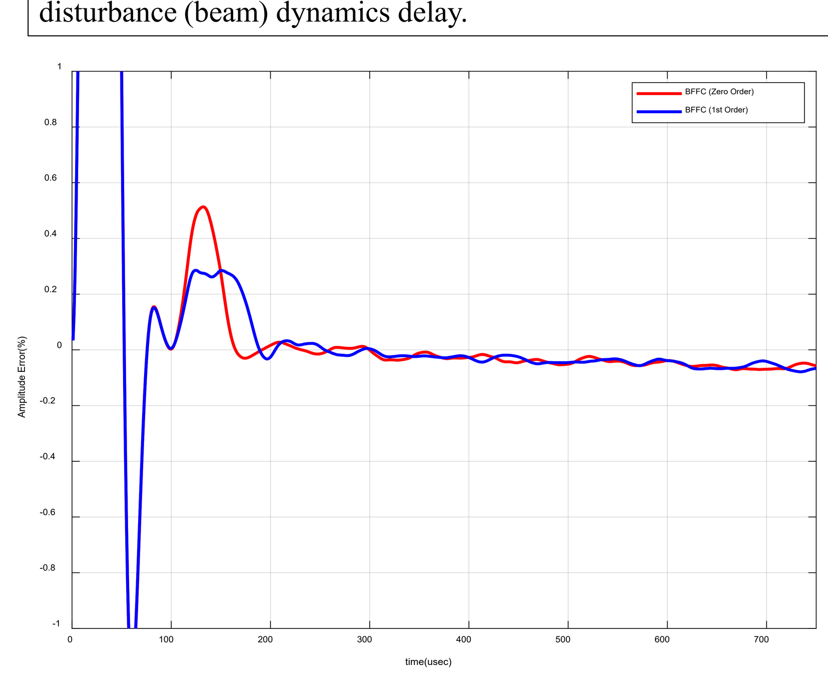




III. Beam Feedforward Control(BFFC)

$$F(s) = \begin{bmatrix} (a_{I,1}s + a_{I,0})e^{-L_{ff}s} & 0 \\ 0 & (a_{Q,1}s + a_{Q,0})e^{-L_{ff}s} \end{bmatrix}$$

Beam Feedforward Controller[2,3]: The structure of the beam feedforward controller is the inverse of the cavity model. $a_{I,1}, a_{I,0}, a_{Q,1}, a_{Q,0}$ are controller parameters to be tuned. L_{ff} is the time delay of the feedforward controller and the ideal value is $L_{ff} = T_{dist} - T_d$ where τ_{dist} is the disturbance(beam) dynamics(represented by D(s)) time constant and T_d is the disturbance (beam) dynamics delay.



Zero Order BFFC does not use the beam derivative information. In BFFC, using the Beam Derivative(First Order SBFFC) is more beneficial. The beam is H- beam and its peak current is 8mA.

IV. Iterative Learning Control(ILC)

Controller: $u_{k+1}^{ILC} = \alpha Q(u_k + Le_k)$

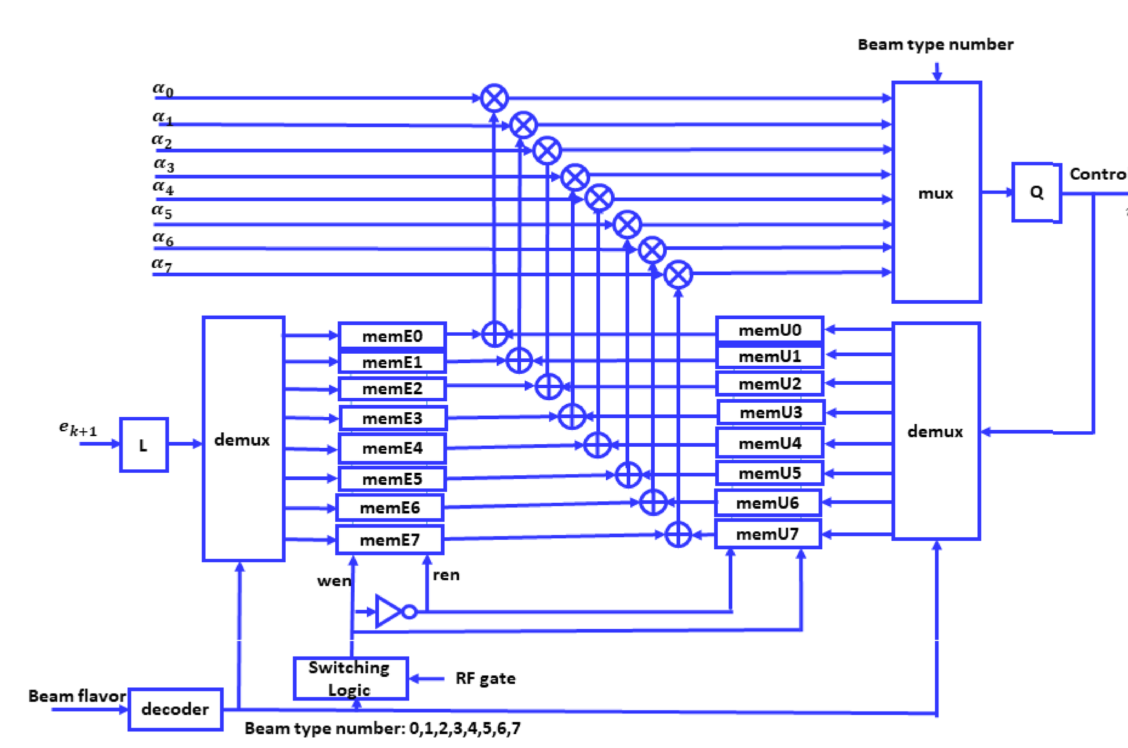
Controller Output Convergence Condition:

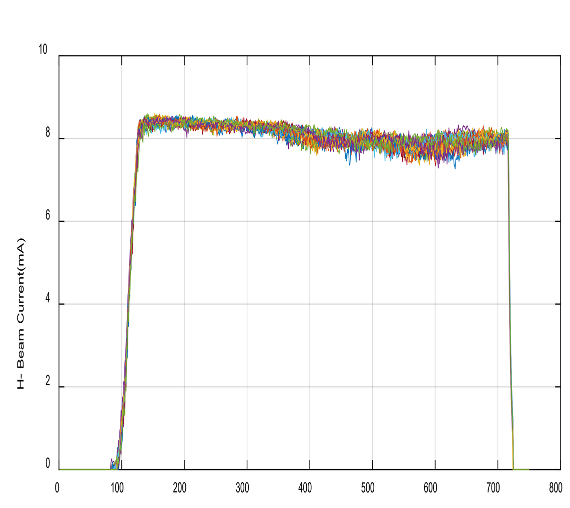
$$\alpha\left\|\frac{Q(1-LG)}{1+GC}\right\|_\infty < 1$$

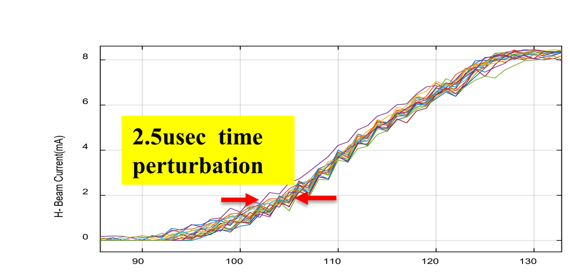
Asymptotic Behavior of the Error:

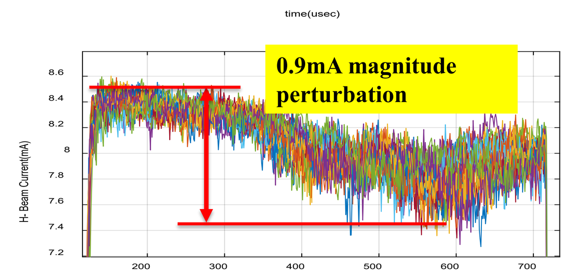
$$\lim_{k\to\infty} E_k = \frac{1-\alpha Q}{1+\mathrm{GC}-\alpha Q(1-LG)}R + \frac{G}{1+\mathrm{GC}-\alpha Q(1-LG)}\left((\alpha Q-1)D - U_{k+1}^{FF}\right)$$

Iterative Learning Controller[4] structure implemented on the LLRF FPGA: The module accommodates 8 beam species[5]. This Module is implemented for I channel. The same module is also implemented for Q channel. Each mem Block (memE0,memE1,.., memU0, memU2,..) consists of the cascade of two FIFOs. By **wen ,** the first FIFOs in memEi, memUi store incoming e_{k+1}, u_{k+1} and e_k, u_k stored in the first FIFOs are shifted to the second FIFOs. The gains α_i, $i = 0,1,2,..7$ are input from EPICS Channel Access(CA) and stored in the FPGA registers.

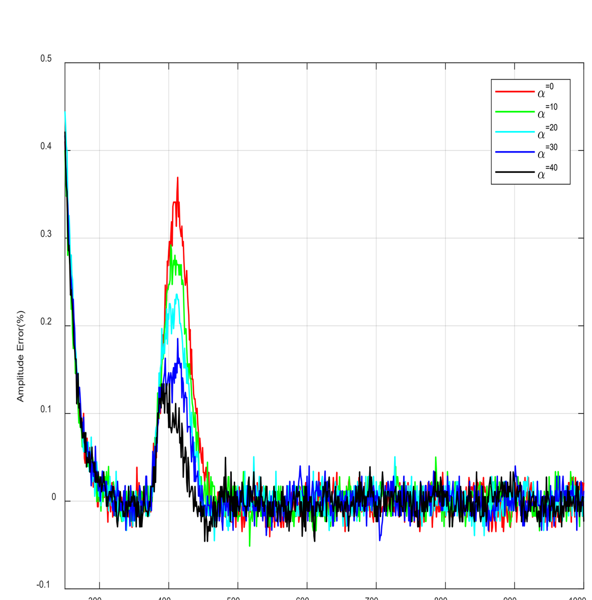


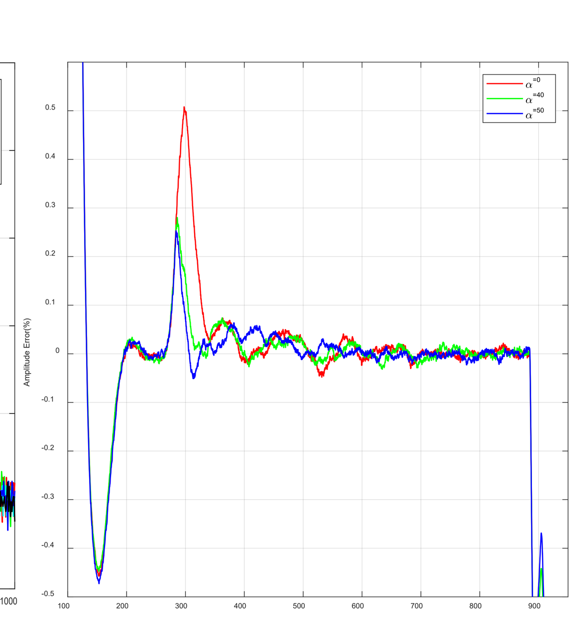






H- Beam Current: The H- beam current is detected using a current transformer. The beam current has 30usec ramp and length of it is 625usec. This detected beam current signal(called beam feedforward signal) is used for beam feedforward control(BFFC). According to the beam current measurement, its insertion time to the cavity has about 2.5usec time domain perturbation, resulting in the same time domain perturbation of cavity field amplitude and phase errors. The suppression of the disturbance(errors) of ILC is based on the assumption that the disturbance is repetitive. The beam(disturbance to the cavity field) is the combination of the repetitive terms and non-repetitive terms. It is believed that ILC suppresses the repetitive terms and PI feedback and BFFC suppress the non-repetitive terms and repetitive-terms.





In order to test the performance of the ILC in case of multi-beams, ILC is implemented at LANSCE 201MHz Drift Tube Linac(DTL).

The performance of the iterative learning controller for 3.6mA H+ Isotope Production Facility (IPF) beam after ILC converges: 625usec long beam with 30usec ramp is loaded at 375usec. The PI feedback controller is the default controller and the zero order beam feedforward controller is applied because the amplitude error without the beam feedforward controller causes the fast protecting resulting in turning off the beam. The static beam feedforward controller is $K_{ff} = 1000$. For the ILC, the L-filter is set 1and the Q-filter pole is 0.305. The error data is obtained inside the field control module(FCM).

The performance of the iterative learning controller for 8.0mA H- 1LTarget (LBEG) beam after ILC converges: 625usec long beam with 30usec ramp is loaded at 375usec. The PI feedback controller is the default controller and the zero order beam feedforward controller is applied because the amplitude error without the beam feedforward controller causes the cavity field errors over the design specifications, resulting in turning off the beam. The static beam feedforward controller is $K_{ff} = 3500$. L-filter is 1. Q-filter pole is 0.305. The amplitude error is obtained with ADL5511[6] .

V. Disturbance Observer(DOB) Based Control

Plant: $y = G(u+d)$

Disturbance Estimate: $\hat{d} = Q_{ob}G_n^{-1}y - Q_{ob}u$

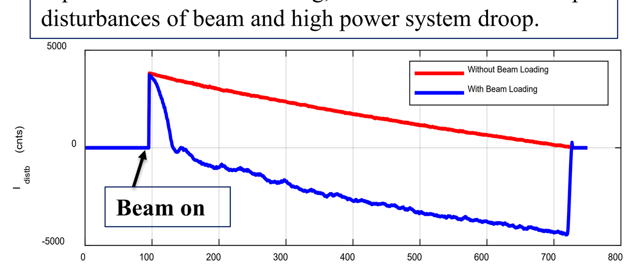
Plant Transfer Function: $G_n(z) = \dfrac{1-P_c}{z-P_c}$

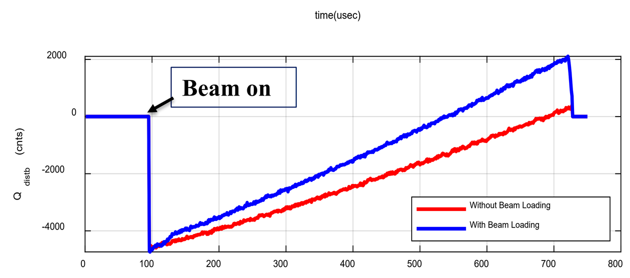
DOB Filter Transfer Function: $Q_{ob}(z) = \dfrac{1-P_{ob}}{z-P_{ob}}$

Causal Implementation of DOB: $Q_{ob}(z)G_n^{-1}(z) = = \frac{1-P_{ob}}{1-P_c}\cdot\left(1+\frac{P_{ob}-P_c}{z-P_{ob}}\right)$

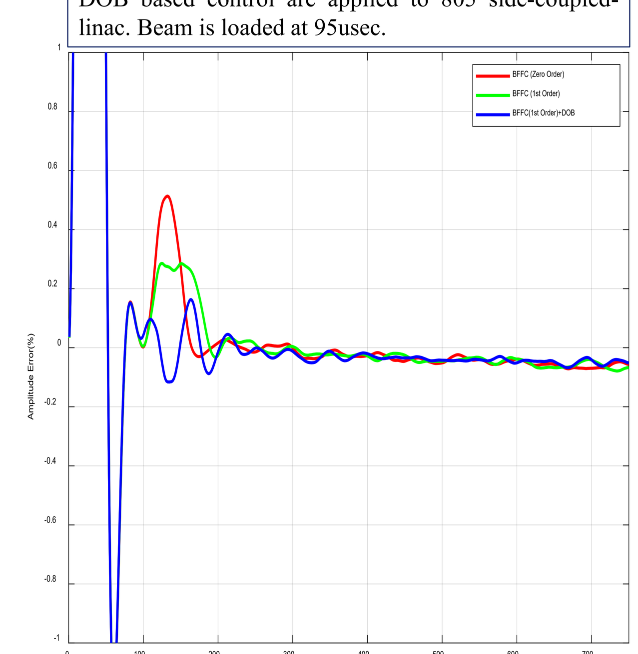
Proper to suppress the non-repetitive disturbances at low frequency[7]. The DOB needs the inverse model of the plant (cavity). In general, the plant, the base-band representation of the cavity is a lowpass filter characteristics and so the inverse of the plant may be anti-causal, which means the implementation of the inverse of the nominal model, G_n^{-1} on the FCM is impossible. Then, instead of G_n^{-1}, $Q_{ob}G_n^{-1}$ is implemented with the design of the disturbance observer Q-filter. It is obvious that the filter, $Q_{ob}(s)$ plays a central role in the disturbance observer based controller. Ideally, to estimate the effect of the disturbance, $Q_{ob}(s)$ should be designed to close to 1 in all of the frequency range. However, this may amplify the high frequency sensor/detector noise. Since the plant has lowpass fillter characteristics, $Q_{ob}(s)$ is designed as a lowpass filter with its relative degree being equal or greater than the relative degree of the plant (model), G_n, so that $Q_{ob}G_n^{-1}$ is implementable. The reason that $Q_{ob}(s)$ is a lowpass filter is that the disturbance, d is of low frequency or medium frequency and the sensor/detector noise is usually of high frequency. As a result, the disturbance observer estimates the disturbance of low frequency or medium frequency but rejects sensor/detector noise of high frequency. The cutoff frequency of $Q_{ob}(s)$ is vital in trading off between the stability and the performance, frequency characteristics of the disturbance, d, and the frequency characteristics of senor/detector noise, etc.. Higher cutoff frequency yields better disturbance attenuation but it increases the sensitivity to the sensor noise[7]. The DOB outputs are multiplied by adjustable gains and applied to add control signals.

DOB Performance: I channel and Q channel disturbance estimates. When there is without beam loading, DOB estimates droops caused by the high power system capbank. With beam loading, DOB estimates the lumped disturbances of beam and high power system droop.

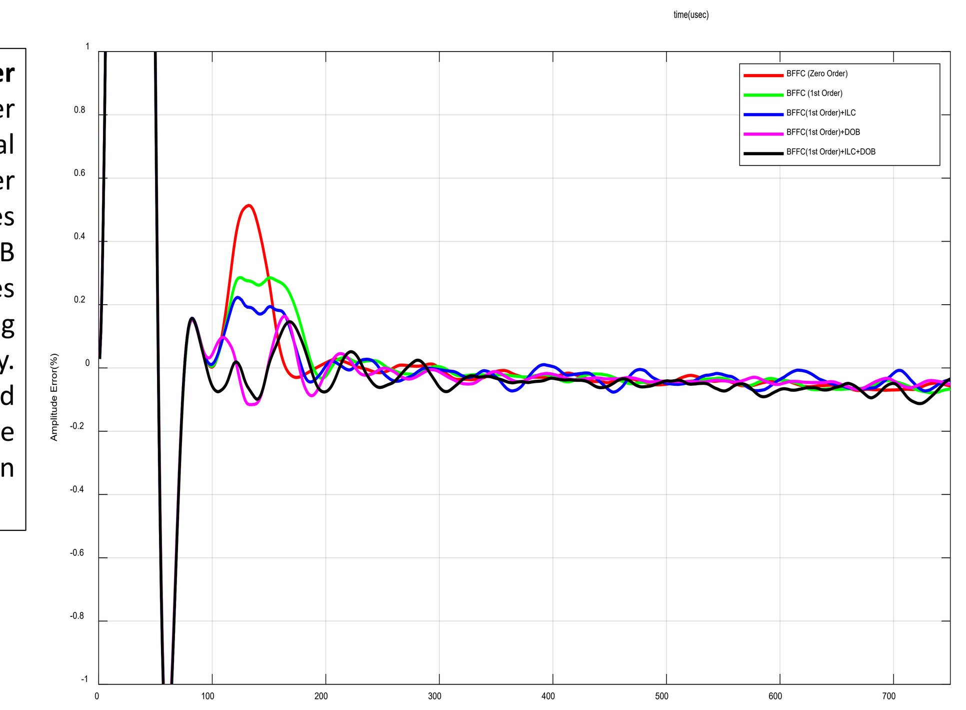




DOB based Controller Performance: SBFFC and DOB based control are applied to 805 side-coupled-linac. Beam is loaded at 95usec.



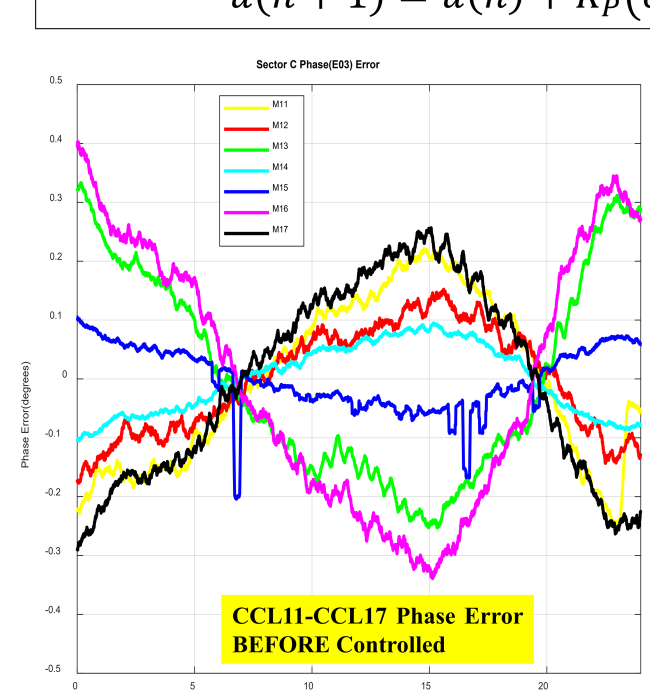
Overall Controller Perforamnce: 1st Order BFFC is more beneficial compared with zero Order BFFC. ILC further reduces the amplitude error. DOB based control improves the beam loading compensation significantly. Both application of ILC and DOB does not improve the performance more than only DOB is applied.

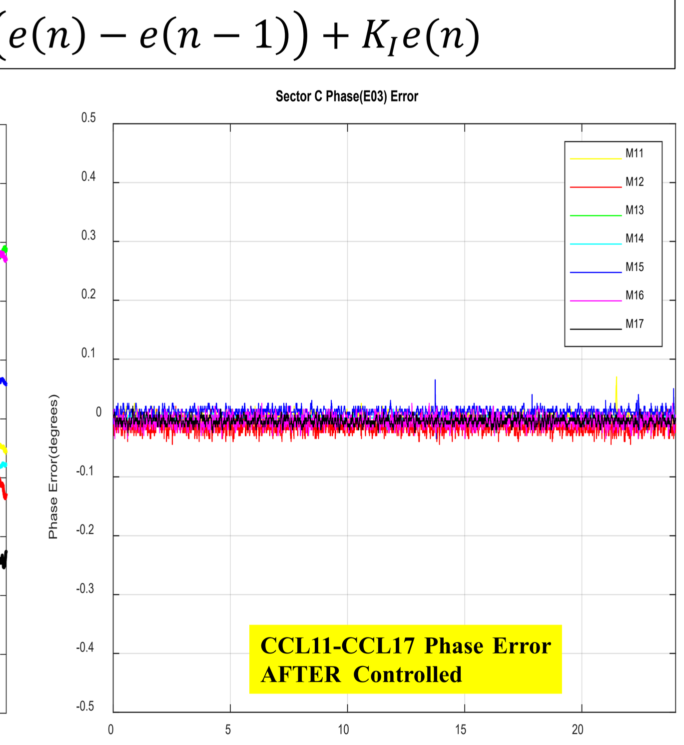


VI. Longterm Phase Stability

Longterm measurement of cavity field phase shows the (pseudo)sinusoidal drift(+/-0.35degrees). The cause of the drift is suspected to the cavity cooling water temperature change, the tunnel temperature drift, etc. In order to compensate for the phase drift, a software(octave m-script) based PI controller is implemented. The controller input is the AD8302[6] RF phase detector output and the controller output is added to the IF drive phase output of FCM.

$$u(n+1) = u(n) + K_P\big(e(n) - e(n-1)\big) + K_I e(n)$$





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