LONGITUDINAL DYNAMIC ANALYSIS FOR THE PROJECT X 3-8 GeV PULSED LINAC

G. Cancelo, B. Chase, Nikolay Solyak, Yury Eidelman, Sergei Nagaitsev
Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

Abstract

The Pulsed Linac requires over 200 9-cell, 1300 MHz cavities packed in 26 ILC type cryomodules to accelerate 1 mA average beam current from 3GeV to 8 GeV. The architecture of the RF must optimize RF power, beam emittance, and energy gain amid a large number of requirement and constraints. The pulse length is a critical issue. Ideally, a 26 ms pulse would allow direct injection into the Fermilab's Main Injector, bypassing the need of the Fermilab's Recicler. High loaded quality factors (QL) are also desirable to minimize RF power. These requirements demand an accurate control of the cavity resonant frequency disturbed by Lorentz Force Detuning and microphonics. Also the LLRF control system must regulate the RF amplitude and phase within tight bounds amid a long list of dynamic disturbances.

INTRODUCTION

The H^- 3-8 GeV LINAC for Project X [1] is optimized for accelerating the synchronous particle at a small negative phase close to the RF peak voltage. At 3 GeV beam β's and transit time factors (TTF) along the 200+ cavity LINAC are near 1and monotonically increasing along z. Although TTF and β_b impact in the longitudinal dynamics most longitudinal problems arise from the fact that, to cut costs, modern accelerators are being designed powering a string of cavities from one klystron. As multiple cavities are connected to a single klystron the setting and control of RF system parameters becomes more complex. A low level RF (LLRF) control loop controls the amplitude and the phase of the klystron's RF power. However, the loop cannot dynamically control individual cavity amplitude and phases. This is further complicated due to Lorentz forces (LFD) and microphonics that severely detune superconducting cavities. One more problem arises from the fact that to achieve the maximum possible acceleration cavities are operated at their maximum operating gradient, close to their quenching limit. Since some disturbances are pulse to pulse repetitive we can use some feedforward compensation. For instance LFD can be minimized at the single cavity level using piezoelectric tuners. The setting of RF cavity parameters such as synchronous phases (Φs), predetuning (Δω) and RF power P_{for_i} and fill time t_0 are very important.

LONGITUDINAL DYNAMICS SIMULATIONS

For small phase-energy oscillations the stability of the longitudinal dynamics can be studied using a Hamiltonian equation (1) relating the phase and energy stability [2] (Figure 1).

$$H_\phi = \frac{Aw^2}{2} + B(\sin\phi - \phi\cos\phi_s) \quad (1)$$

where the first term represents the kinetic energy of the particle and the second term the potential energy. A and B are constants:

$$A = \frac{2\pi}{\beta_s^3\gamma_s^3\lambda}, \qquad B = \frac{qE_0T}{mc^2}$$

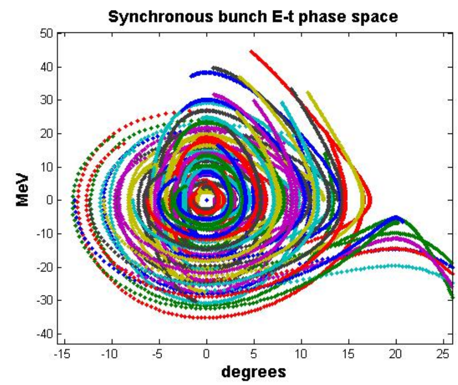

Figure 1: Synchronous bunch E-T phase space.

As shown in Figure 2, at 3 GeV the small amplitude oscillation frequency is 1.24 MHz (i.e. 0.8μs period). The oscillation frequency slows down as energy increases.

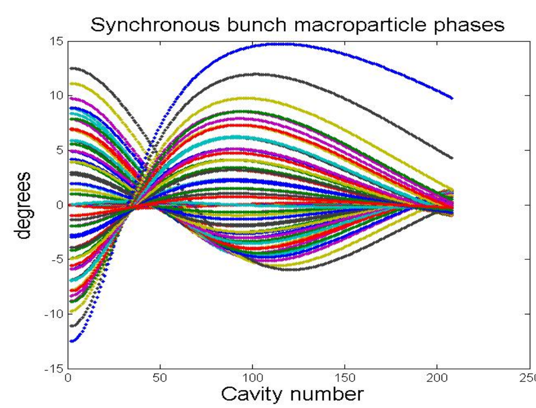

Figure 2: Synchronous bunch macroparticle phases.

$$\omega_{osc} = \sqrt{\frac{\omega_0 E_0 TTF \sin(\phi_s) c}{mc^2 \beta_s \gamma_s^3}}$$

$\phi_s = -10°$	*sync_phase*
$TTF = 0.97$	*TransitTimeFactor*
$E_0 = 3GeV$	*Init.Enage*
$\beta_s = 0.95$	*syncbeta*
$\omega_0 = 2\pi 1.3GHz$	*RFfreq*

These simulations are performed using a bunched beam represented by 73 macroparticles and a Gaussian profile in E and t. The total number of particles is 6.24 10^{12} per mA of current.

The simulated conditions are:

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#cancelo@fnal.gov

- Average gradient amplitude 25 MV/m.
- 13 RF Stations: 2 cryomodules with 8 cavities/cryomodule and a total of 16 cavities/RF Station.
- Total Energy gain ~5 GeV.
- Beam current: 1 mA (try also 2 mA).
- Beam phase: -10 degrees.
- RF pulse: 4.3 to 30 ms flattop.
- Fill Time: 4.243 ms.
- Qload: up to a maximum of 10^7.
- R/Q=1036 Ohm/cav.

At 25MV, I_b=1mA and (R/Qo)=1036Ω the Q_L for power matching is 2.5e7, implying a $BW_{1/2}$ of 26Hz. In order to better deal with LFD and u-phonic disturbances a $Q_L=1x10^7$ has been set.

Major concerns studied are:

- Energy spread inside the RF station. Despite a well regulated VS there may be emmitance grow and beam loss due to tilts in amplitudes and phases of individual cavities under the same close loop.
- LFD: peak to peak detuning, in particular for long pulses (4, 8 and 30ms flattops)
- Impact of fill time in LFD.
- Active compensation.
- Maximum RF accelerating energy: cavity gradients close to quenching limits.
- Influence of cavity gradient spread in the RF station.
- Optimum cavity loaded quality factors (QL) as a function of cavity gradients.

CAVITY ELECTRICAL AND MECHANICAL MODELS

The electrical model is represented by a 1st order differential equation modeled with 2 state-variables, the I and Q components of the cavity voltage.

$$\begin{bmatrix} \dot{V}_r \\ \dot{V}_i \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix} \cdot \begin{bmatrix} V_r \\ V_i \end{bmatrix} + \begin{bmatrix} \omega_{1/2} R_L \\ \omega_{1/2} R_L \end{bmatrix} \cdot \begin{bmatrix} I_r \\ I_i \end{bmatrix} \quad (2)$$

The model is time-varying because the detuning (Δω) varies along the pulse. Δω is coupled through the mechanical model. The mechanical model is represented by 2nd order differential equation of the cavity detuning as a function of the square of the gradient for each mechanical resonant mode.

$$\frac{d^2(\Delta\omega_m)}{dt^2} + \frac{\omega_m}{Q_m}\frac{d(\Delta\omega_m)}{dt} + (\omega_m)^2\,\Delta\omega_m = (\omega_m)^2\,2\pi K_m V^2(t)$$

$$\Delta\omega_m = \sum_{m=1}^{3} \Delta\omega_m \qquad m = 1,2,3$$

ILC type 9-cell niobium cavities detune about 600Hz at 25MV by effect of LFD. This number is prohibitive in terms of RF power required. We assume that LFD can be controlled to 60Hz or better. We also assume a microphonic detuning of ±5Hz RMS (Figure 3).

The LFD is a function of V^2. Longer flattops do not imply worse LFD after the first minimum which occurs at 4ms. Predetuning the cavities increases the LFD oscillations although shortens the time of the first minimum to 2ms (Figure 3).

A possible way for reducing the LFD using the RF is to make a smoother Off to On power transition. For instance if instead of applying a power step we ramp the power during part or all the fill time, the detuning becomes,

$$\Delta\omega = \frac{V_0^2}{t_{fill}^{\;2}}\left[t^2 - at + \frac{e^{-t/\tau}}{\sqrt{4Q_m^{\;2}-1}}\left(1-\sin\left(\sqrt{4Q_m^{\;2}-1}\,\omega_m t + \phi_0\right)\right)\right]$$

For $0<t<t_{fill}$. And where a is the slope of the ramping power. For small t we can achieve a substantial LFD reduction at the expense of a longer fill time. However single digit peak to peak LFD numbers can, so far, only be achieved using piezotuners.

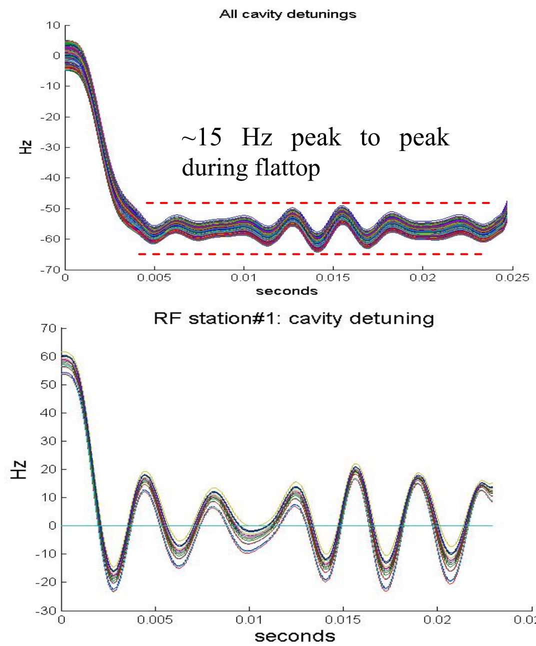

Figure 3: All cavity detunings (upper trace) and with pre-detuning (lower trace).

RF PARAMETER SETTING

A key problem is the control of a string of cavities operating at different gradients, synchronous phases and beam loading. A real life example we simulated using the gradients of the two highest accelerating cryomodules at DESY-FLASH (ACC6 and ACC7), which average 24.8 and 27.5 MV/cav and a total of ~420MeV. The RF station gradient spread can be about 20% of the mean gradient.

A simplistic option is to operate all cavities at the same gradient and loaded Q's (Q_L), below the gradient of the cavity with the lowest quenching limit. This option avoids individual cavity tilts at all beam loading conditions. The advantage is simplicity. We can use a fix RF distribution and, in principle, fix couplers, but we give up 20% of the gradient.

A fixed proportional power distribution allows individual gradients to approach higher limits. However, this approach must be accompanied with adjustable couplers to be able to flatten individual cavities for each beam loading.

Cavity tilts arise due to mismatch between RF, beam and cavity parameters including magnitude, phase and detuning.

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Cavity tilts force us to lower gradients to avoid quenches. Cavity tilts and cryomodule misalignment generate transverse kick and large emitance growth. And tilts are proportional to the flattop length.

The most common approach for finding optimum longitudinal parameters is to consider zero reflected power at beam injection [3]. During the fill time of the RF pulse the cavity gradient increases exponentially from 0 to V_{cav0} and, if at beam injection, the RF forward power equals the beam power then the system suddenly enters the steady state and a flat pulse is achieved. Unfortunately this is seldom the case when the RF station operates cavities at different gradients, synchronous phases and beam loadings. The steady state approach finds:

$$\beta_{opt} = 1+\frac{2RI_{b0}}{V_{cav}}\cos\phi_s \quad , \quad \varphi_{opt} = -\phi_s, \quad P_{ref\_cav}=0. \qquad (3)$$

A simulation with parameters calculated by (3) and LFD show gross cavity amplitude and phase deviations during the pulse which translates into up to 5MeV energy spread between the head and the tail of the bunch train (Figure 4). Even when the RF Vector Sum is well control by the feedback loop.

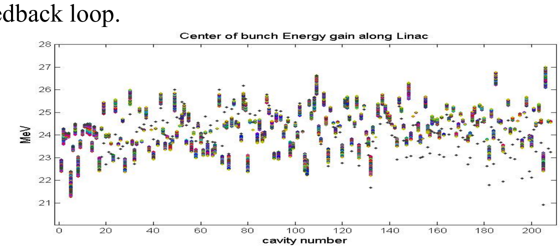

Figure 4: Simulation of bunch energy.

As a consequence the zero reflected power premise is not met either. An alternative approach is using the transient response of the cavity equations and setting $V_{cav\_i}=0$ for $t>T_{fill}$, without constraining the reflected power [4].

The RF system voltages and currents are modelled by equations (2).

For fix or null LFD the system is linear, the cavity voltage is the superposition of the cavity response to the generator and beam currents (power) $I_g e^{j\theta}$ and $I_b e^{j\pi}$.

The solution to equation (2) is given by:

$$\begin{pmatrix}V_r\\V_i\end{pmatrix} = \frac{\omega_{12}R_L}{\omega_{12}^2+\Delta\omega^2}\left\{e^{-\omega_{12}t}I_g\begin{pmatrix}-\omega_{12}\cos(\Delta\omega t+\theta)+\Delta\omega\sin(\Delta\omega t+\theta)\\-\Delta\omega\cos(\Delta\omega t+\theta)-\omega_{12}\sin(\Delta\omega t+\theta)\end{pmatrix}u(t)+I_g\begin{pmatrix}\omega_{12}\cos\theta-\Delta\omega\sin\theta\\\Delta\omega\cos\theta+\omega_{12}\sin\theta\end{pmatrix}\right.$$
$$\left. e^{-\omega_{12}(t-t_o)}I_b\begin{pmatrix}-\omega_{12}\cos\Delta\omega(t-t_o)+\Delta\omega\sin\Delta\omega(t-t_o)\\-\Delta\omega\cos\Delta\omega(t-t_o)-\omega_{12}\sin\Delta\omega(t-t_o)\end{pmatrix}u(t-t_o)-I_b\begin{pmatrix}\omega_{12}\\\Delta\omega\end{pmatrix}u(t-t_o)\right\} \qquad (4)$$

Where u(t) is the Heaviside function (i.e. u(t)=1 $t\geq 0$ and 0 otherwise).

To obtain a flattop at the injection time $t=t_0$ we must eliminate the time dependency in equation (4). That is achieved by making

$$I_g = e^{\omega_{12}t_o} I_b \qquad (5a) \qquad \text{and} \qquad \Delta\omega = -\theta/t_0 \qquad (5b)$$

Equations (5a,b) guarantee a flattop for $t\geq t_0$. The appropriate value for the flattop amplitude and phase can be obtained from equation (4) at $t=t_0$- given by

$$\begin{pmatrix}V_r\\V_i\end{pmatrix}_{t=t_o} = \frac{\omega_{12}R_L}{\omega_{12}^2+\Delta\omega^2}\left\{e^{-\omega_{12}t_o}I_g\begin{pmatrix}-\omega_{12}\\-\Delta\omega\end{pmatrix}+I_g\begin{pmatrix}\omega_{12}\cos\theta-\Delta\omega\sin\theta\\\Delta\omega\cos\theta+\omega_{12}\sin\theta\end{pmatrix}\right\} \qquad (6)$$

Using the tuning angle equation $\tan\psi=\frac{\Delta\omega}{\omega_{12}}$, the cavity voltage amplitude and phase are given by:

$$|V_c| = \frac{R_L I_b}{1+\tan^2\psi}\sqrt{\left(-1+e^{\omega_{12}t_o}(\cos\theta-\tan\psi\sin\theta)\right)^2+\ldots+\left(-\tan\psi+e^{\omega_{12}t_o}(\tan\psi\cos\theta+\sin\theta)\right)^2} \qquad (6)$$

$$\phi_s = \tan^{-1}\left(\frac{\tan\psi\cos\theta+\sin\theta-\tan\psi e^{-\omega_{12}t_o}}{\cos\theta-\tan\psi\sin\theta-e^{-\omega_{12}t_o}}\right) \qquad (7)$$

Equations (6) and (7) have 3 unknowns: the RF cavity phase θ (i.e. ψ), β (i.e. Q_L) and t_0. Both R_L and the half bandwidth ω_{12} are a function of β. (6) and (7) with constrains (4) and (5) are solved for for θ and β for a fix t_0. Also t_0 can be used to optimize the reflected power. Figure 5 shows how amplitudes and phases are maintained fairly flat even in high LFD and RF closed loop.

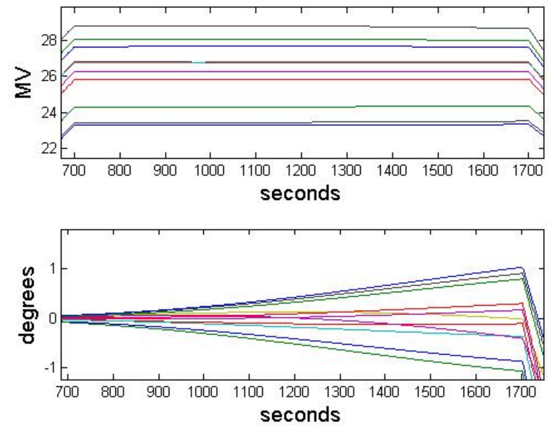

Figure 5: Stabilized amplitude and phases.

As part of the ILC 9mA experiment at DESY-FLASH we have reduced tilts even further using an iterative procedure that fine tunes the Q_L's. Tilts better 0.2% RMS over 800us have been obtained in an RF station with 16 cavities [5].

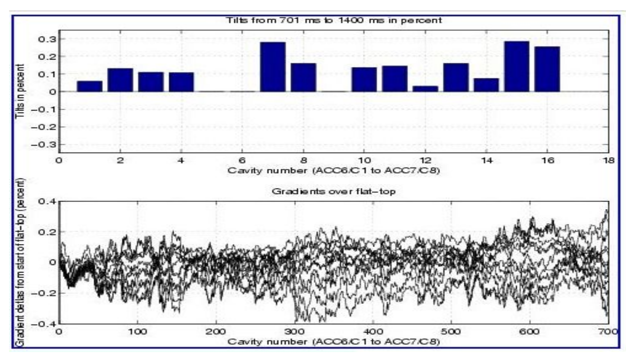

Figure 6: Cavity tilts in FLASH ACC 6 and 7.

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