ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM047

RF FEEDBACK SIMULATION FOR DIAMOND-II USING ELEGANT

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Abstract

The Diamond-II storage ring will utilise normal conducting main cavities and a passive superconducting harmonic cavity in its RF system. To evaluate the effects of bunch lengthening and lifetime gain from the harmonic cavity for different filling patterns, transient beam loading effects need to be studied. When simulating these effects with ELEGANT, RF feedback for the main cavities must be defined using sets of infinite impulse response (IIR) filters. This paper describes the method used to convert proportional-integral (PI) feedback parameters representative of the RF feedback implemented at Diamond into equivalent ELEGANT settings and presents simulation results demonstrating the effectiveness of the RF feedback. Transient beam loading effects for the standard and hybrid filling pattern are also studied.

INTRODUCTION

An upgrade is planned for the Diamond Light Source to replace the existing storage ring with a multi-bend achromat lattice. This will reduce emittance and provide higher brightness for scientific users [1]. The Diamond-II storage ring will use a passive superconducting harmonic cavity to lengthen the bunch for improved lifetime and stability. Transient beam loading effects from the main and harmonic cavities need to be studied to verify the effectiveness of bunch lengthening from the harmonic cavities [2].

To study the transient beam loading effects, both the main and harmonic cavities are modelled using the RFMODE element in ELEGANT. The RF feedback for the main cavities must also be set to maintain the desired cavity voltage and phase. In ELEGANT, this is achieved using IIR filters [3,4], while at Diamond, a PI feedback is used. This paper introduces the implementation of a PI feedback using IIR filters in ELEGANT. Simulations are also conducted to test the effectiveness of the new RF feedback settings. Transient beam loading effects for the standard and hybrid filling pattern are also studied.

PI FEEDBACK SETTING IN ELEGANT

PID feedbacks are widely used in different control scenarios, where P, I and D stand for proportional, integral, and differential, respectively. The feedback input is usually some error $x(t)$ with respect to the set value or goal value, the output is calculated by [5]

$$y(t) = K_p x(t) + K_i \int_0^t x(\tau) d\tau + K_d \frac{dx}{dt} \tag{1}$$

The transfer function in the s domain can be obtained by Laplace transform on the input and output:

$$H(s) = \frac{L[y(t)]}{L[x(t)]} = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \tag{2}$$

where s denotes the Laplacian complex frequency domain.

On the other hand, the IIR filter deals with a discrete signal, where the output is calculated by [3]

$$\begin{aligned} a_0 y(n) &= b_0 x(n) + b_1 x(n-1) + \cdots + b_P x(n-P) \\ &\quad - a_1 y(n-1) - a_2 y(n-2) - \cdots - a_Q y(n-Q), \end{aligned} \tag{3}$$

where $x(n)$ represents the input at step n, and by default $a_0 = 1$. The order of the IIR filter is defined as the larger of P and Q. The coefficients b_i and a_i are referred to as the numerator and denominator, respectively in ELEGANT. For the IIR, there is also a transfer function obtained by performing a Z transform on both the input and output by

$$H(z) = \frac{Z[y(n)]}{Z[x(n)]} = \frac{\sum_{i=0}^{P} b_i z^{-i}}{1 + \sum_{j=1}^{Q} a_j z^{-j}} \tag{4}$$

where z represents the complex frequency domain of the Z transform.

To gain a connection between the continuous s domain and discrete z domain, a bilinear transform can be adopted, which is a first order approximation: [6]

$$z = e^{sT} = \frac{e^{sT/2}}{e^{-sT/2}} \approx \frac{1 + sT/2}{1 - sT/2} \tag{5}$$

where T is the feedback period, and the inverse transform is

$$s = \frac{2}{T} \frac{1 - z^{-1}}{1 + z^{-1}}. \tag{6}$$

Inserting this into the transfer function for the PI feedback (after setting $K_d = 0$ in the PID feedback), the corresponding transfer function in the discrete z domain becomes:

$$H(z) = \frac{K_p + K_i T/2 + (K_i T/2 - K_p) z^{-1}}{1 - z^{-1}}. \tag{7}$$

This corresponds to an IIR filter:

$$\begin{aligned} y(n) &= \left(K_p + \frac{K_i T}{2}\right) x(n) \\ &\quad + \left(\frac{K_i T}{2} - K_p\right) x(n-1) + y(n-1) \end{aligned} \tag{8}$$

The same set of IIR filter coefficients will be used for both the IQ components of the main cavities. The adjustment of cavity voltage is realised by adjusting the generator current:

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$$I_{g,I} = I_{g0,I} + \text{IIR}\left(\frac{V_{I,\text{set}} - V_I}{R_{s,\text{eff}}}\right)$$
$$I_{g,Q} = I_{g0,Q} + \text{IIR}\left(\frac{V_{Q,\text{set}} - V_Q}{R_{s,\text{eff}}}\right), \quad (9)$$

where the subscripts 'I' and 'Q' represent the I and Q components respectively. I_{g0} is the initial generator current, V_{set} is the voltage IQ component set value, and $R_{s,\text{eff}}$ is the effective shunt impedance.

EFFECTIVENESS OF THE NEW RF FEEDBACK SETTING

After studying a range of IIR filter coefficients for the ELEGANT tracking, the IIR coefficient sets

$$a_0 = 1, a_1 = -0.9999$$
$$b_0 = 1.5, b_1 = -0.5$$

were found to keep the cavity voltage and phase stable whilst remaining consistent with the Diamond implementation. This coefficient set corresponds to a PI feedback with parameters

$$K_p = 1, K_i T/2 = 0.5$$

according to Eq. (3) and Eq. (8). The parameter a_1 is chosen to be a value slightly above -1 to avoid a intrinsic instability from the IIR filter.

A beam current ramping simulation was conducted using these settings, in which the beam current was linearly increased from 0 to 300 mA over 80,000 turns. The standard filling pattern of 5 trains of 180 bunches was assumed. The main and harmonic cavities are set using the RFMODE in ELEGANT. During these studies the main cavities were modelled as 8 identical units, although for Diamond-II the actual number has been reduced to 7 main cavities for the first phase. The RF feedback was configured to update every two revolution turns, consistent with the existing systems in use at Diamond.

The simulation results are illustrated in Fig. 1. By implementing these feedback settings, the cavity voltage and phase remain stable at their nominal values while the stored current is increased. This is achieved by adjusting the input generator current and phase. The maximum generator current change in one feedback step is calculated to be 13.5 µA, while the maximum phase change is 4.7 µrad. These changes are relatively small and are considered feasible for this fast-ramping process. In reality, during injection the increase in beam current would occur over a much longer period than 100,000 turns.

TRANSIENT BEAM LOADING EFFECTS

With the RF feedback settings now consistent with the Diamond PI feedback, transient beam loading effects were studied for a selection of cases. The standard filling pattern at nominal operation has already been studied in [1,7], and the transient beam loading effect has a similar result compared with the previous results.

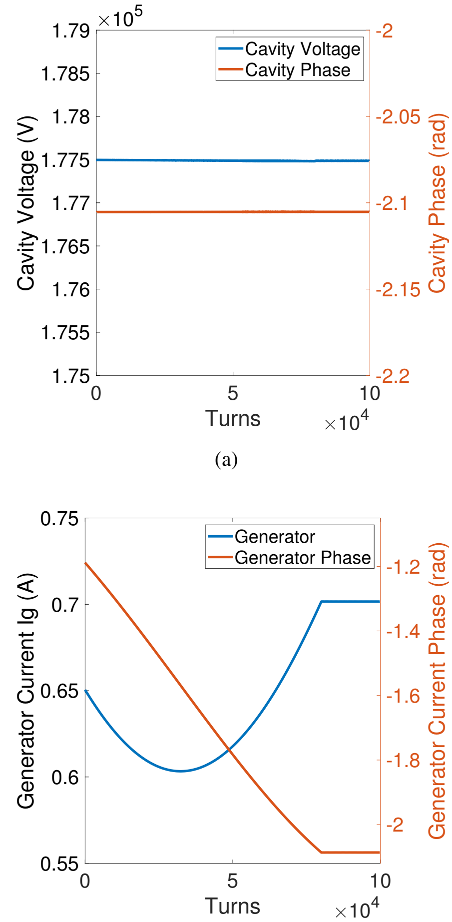

Figure 1: Injection simulation for the RF feedback. (a) Variation in main cavity output voltage and phase during the ramp. (b) Input generator current and phase set by the RF feedback.

Different hybrid filling patterns are required by timing mode users, with four different half gap bucket numbers of 10, 35, 75, and 100. Transient beam loading effects from hybrid filling patterns with 1 or 2 trains have been studied, keeping the total number of bunches within the available 934 RF buckets. Figure 2 shows the transient beam loading effects for the standard filling pattern and hybrid filling patterns with a 100-bucket half gap, with 1 train and 2 trains. Compared to the standard filling pattern, the maximum bunch centroid offset is larger and the bunch lengthening effect is lower.

The lifetime gain relative to the nominal bunch in a standard filling pattern is calculated using the equation: [1]

$$\frac{\tau_{HC}}{\tau_0} = \frac{q_{\text{nominal}}}{q_{\text{bunch}}} \frac{\int \rho_0^2(z)dz}{\int \rho_{HC}^2(z)dz}, \quad (10)$$

where τ stands for lifetime, q_{nominal} is the nominal bunch charge in the uniform filling pattern (0.6 nC) and $\rho(z)$ stands for longitudinal bunch profile. Figure 3 displays the bunch centroid and lifetime gain for different hybrid filling patterns. The error bars indicate the range of bunch centroid or

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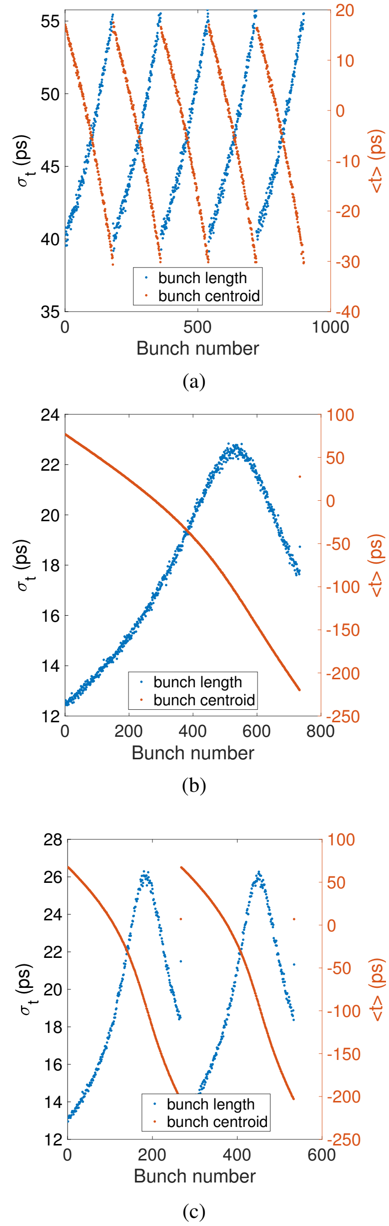

Figure 2: The bunch length and bunch centroid distribution of different filling patterns. (a) Standard filling pattern (5 trains, 7-bucket gaps). (b) Hybrid filling pattern of 1 train, 100-bucket half gap. (c) Hybrid filling pattern of 2 trains, 100-bucket half gap.

lifetime gain over all bunches, while the dot represents the average value. As the half gap length increases, the range of bunch centroid offsets also increases and the average lifetime gain decreases. Electron loss rates currently assumed in Diamond-II for radiation safety purposes are based on a minimum lifetime of 4 hours, and the nominal lifetime is around 2 hours without harmonic cavity. This means that the lifetime gain from the harmonic cavity must be larger than a factor 2. For hybrid filling patterns of 35, 75, and 100 buckets half gap, additional measures such as reducing beam current or increasing vertical emittance will be needed to increase the lifetime.

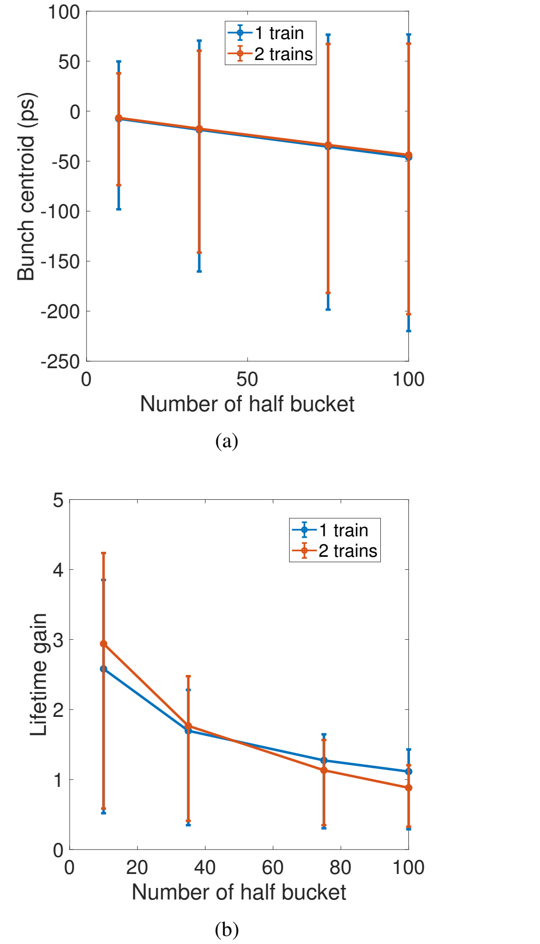

Figure 3: The bunch centroid (a) and lifetime gain (b) of the different hybrid filling patterns.

CONCLUSIONS AND FUTURE WORK

In the ELEGANT simulations for Diamond-II, a PI feedback has been implemented using IIR filters to study transient beam loading. Starting from appropriate PI feedback coefficients, the cavity voltage and phase can be stabilised with feasible adjustments to the generator current and phase. The new RF feedback implementation has been used to study transient beam loading effects for a variety of filling patterns. For hybrid filling patterns with large half bucket lengths, additional measurements are necessary to meet the lifetime gain requirement.

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