THE IMPACT OF BEAM LOADING TRANSIENTS ON THE RF SYSTEM AND BEAM BREAKUP INSTABILITIES IN ENERGY RECOVERY LINACS

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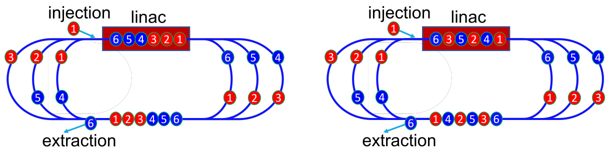
Abstract

In multi-turn Energy Recovery Linacs (ERLs), the filling pattern describes the order that which bunches are injected into the ERL ring. The filling patterns and recombination schemes together can create various beam loading patterns/transients, which can have a big impact on the RF system, namely the cavity fundamental mode voltage, required RF power, and beam breakup instability. In this work, we demonstrate one can lower the cavity voltage fluctuation and rf power consumption by carefully choosing the right transient by using an analytical model and simulation.

INTRODUCTION

Recirculating Energy Recovery Linac (ERL) is a promising technology as it combines the high brightness of conventional linacs with the high average powers of the storage rings. Unlike conventional linacs, the used bunches are not deposed directly, but rather decelerated in accelerator cavities [1], and their kinetic energy (KE) is recovered as the RF field energy of the cavities. As a result much less RF power is required to operate the ERLs compared to conventional linacs.

The accelerating and decelerating bunches in the multi-turn ERL can be grouped differently [2] to form various beam loading transients (or patterns) as shown in the examples in Fig. 1. The red/blue circles are accelerated/decelerated bunches and the number indicates their turn number. The sub-figure (a) shows a beam loading pattern where 3 accelerated bunches are followed by 3 decelerated bunches, while (b) shows accelerating and decelerating bunches come alternatively. In a 6-turn (3 accelerating and 3 decelerating) ERL, 6 bunches form a bunch packet, and many of these packets fill up the ring.



(a) (b)

Figure 1: Beam loading patterns: (a) {123456} and (b) {142536}.

We will show one can minimize cavity voltage fluctuations and required RF power by carefully selecting the right beam loading patterns [3]. Lower cavity voltage fluctuations would improve beam stability and lower required RF power would reduce the energy consumption of the ERL. This has significant implications on beamline design as the beam loading patterns are determined primarily by the beamline topology and bunch recombination schemes.

BEAM LOADING PATTERNS

Beam loading patterns can be of two types depending on whether the bunches change their RF buckets. Generally, bunches are injected in every x RF cycle, and we refer to this x RF cycle as one RF bucket (or one intra-packet block). If the bunches don't change their RF buckets, the turn order in the bunch packet changes turn by turn, and we refer to this as the First In First Out (FIFO) scheme. In this scheme, bunches are injected into different RF buckets in every turn, which would require a complicated bunch injector with variable injection intervals. Currently, ERLs use various recombinations to maneuver the bunches between different RF buckets to maintain the bunch orders so we will refer to this as Sequence Preserving (SP) scheme. Recombination is achieved through path-length-differences to delay bunches differently, as can be seen in Fig. 1.

For FIFO schemes, the beam loading pattern changes turn by turn, so it is convenient to describe FIFO schemes by their filling pattern, which describes their filling order. We will use square brackets to indicate filling patterns. For example, filling pattern [123456] would describe the 1st bunch is injected to the 1st RF bucket, 2nd bunch is injected to the 2nd bucket, and so on so forth. Filling pattern [142536] would describe the 1st bunch is injected to the 1st RF bucket, 2nd bunch is injected to the 3rd bucket, and so on so forth. The number in the bracket is the bunch number, which describes the injection order. The index in the bracket is the RF bucket number.

In SP patterns, however, it is convenient to use beam loading patterns to describe them as the beam loading pattern does not change. We will use curly brackets to indicate beam loading patterns. For example, beam loading pattern {142536} would describe the 1st bunch passing through the cavity is at the 1st turn, the 2nd bunch is at 4th turn, and so on so forth. The number in the bracket is a bunch turn number, which describes the injection order. The index in the bracket is the RF bucket number.

If we call 1st bunch's RF bucket as the 1st RF bucket, for a N-turn ($N/2$ up and $N/2$ down turns) ERL, there are $(N-1)!$ permutations of patterns. Therefore, there are 120 FIFO filling patterns and SP beam loading patterns for a 6-turn ERL. The pattern number i is used to indicate 120

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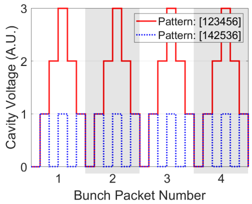


Figure 2: Cavity voltage fluctuations by different beam loading patterns.

permutations of [2 3 4 5 6] and related to the filling pattern F_i as

$$\begin{aligned} F_1 &= [1\ 2\ 3\ 4\ 5\ 6], \\ F_2 &= [1\ 2\ 3\ 4\ 6\ 5], \\ &\vdots \\ F_{120} &= [1\ 6\ 5\ 4\ 3\ 2]. \end{aligned} \tag{1}$$

Similar naming convention also applies to the beam loading pattern P_i.

BEAM LOADING

The accelerated bunches take energy away from the cavity and lower cavity voltage, and conversely, decelerating bunches increase cavity voltage. As each packet has equal numbers of accelerating and decelerating bunches, the net beam loading effect of all packets is zero. However, the cavity voltage fluctuation within a packet can vastly differ depending on the patterns, as shown in Fig. 2. The $\{123456\}$ pattern has larger cavity fluctuation than $\{142536\}$ as it has 3 consecutive bunches taking energy from adding energy to the cavity. The RF power required can also be pattern dependent, but the interaction between cavity voltage and RF system is more complicated as it contains feedback between the two and needs to be studied by beam loading simulations.

The stored RF energy U_{stored} in the cavity is

$$U_{stored} = \frac{V_{cav}^2}{\omega\left(\frac{R}{Q}\right)}, \tag{2}$$

with V_{cav} being the cavity voltage and $\frac{R}{Q}$ being the shunt impedance of the cavity divided by its Q-factor. The change in stored energy from a particle bunch passing through at phase ϕ is

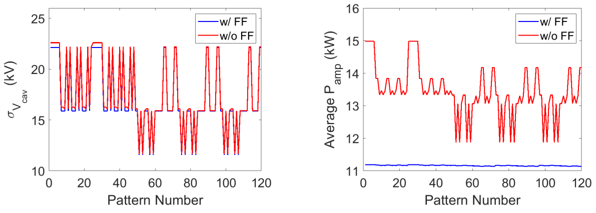
$$\delta U_{stored} = \frac{2V_{cav}\delta V_{cav}}{\omega\left(\frac{R}{Q}\right)} = -q_{bunch}V_{cav}\cos(\phi). \tag{3}$$

Therefore, the change in cavity voltage from beam loading is given as

$$\delta V_{cav} = -\frac{q_{bunch}}{2}\omega\left(\frac{R}{Q}\right)\cos(\phi), \tag{4}$$

Table 1: Simulation Parameters

Machine Parameters	**value**
bunch charge q_{bunch}	18.4 nC
RF cycles per bucket	10
bunches per packet	6
number of bunch packets	20
circumference	360 m
revolution time	1.2 µs
number of turns tracked	96
tracking time duration	121 µs
Cavity Parameters	
cavity voltage (V_0)	18.7 MV
R/Q	400
RF frequency	1 GHz
LLRF Parameters	
latency	1 µs
digital sampling rate	40 MHz
closed-loop bandwidth	2.5 MHz
proportional controller gain G_p	1000
integral controller gain G_i	1
maximum amplifier power	800 kW



(a) (b)

Figure 3: Cavity voltage (a) and average amplifier power (b) with (w/ FF) and without (w/o FF) feed forward.

The cavity voltage is expressed with a complex number, where the real part is the electric field and the imaginary part is a magnetic field. Therefore, δV_{cav} is added to the real part of the RF field. When $\phi = 0$, the cavity accelerates the bunches and V_{cav} drops. Conversely, when $\phi = 90°$, the cavity decelerates bunches, and hence its voltage increases.

SIMULATION

Setup

The simulation parameters are shown in Table 1 for a 6-turn ERL. A high bunch charge is used to accentuate the beam loading effect.

Simulation Results

RF Control System With and Without Feed Forward Simulation results with and without feed forward are given in Fig. 3 for all SP patterns. The cavity voltage fluctuations $\sigma_{V_{cav}}$ and amplifier power P_{amp} are smaller with feed forward.

We plotted the cavity voltage and amplifier power for pattern number 51 with and without feed forward in Fig. 4.

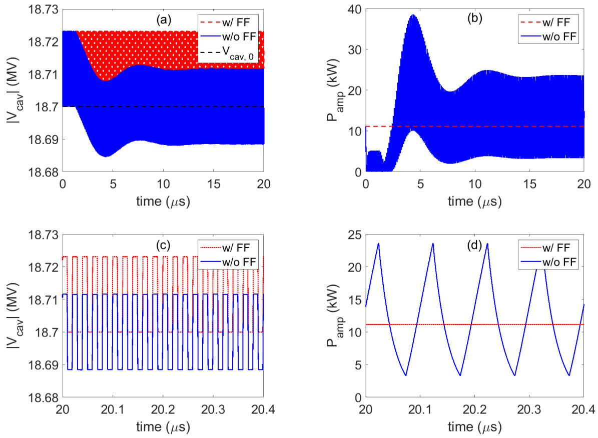
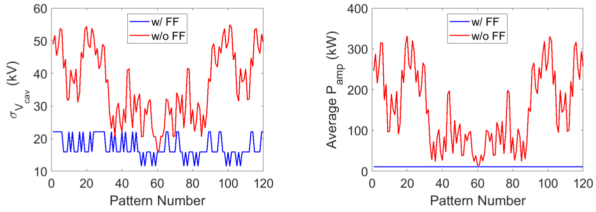


Figure 4: Simulation results with and without feed forward pattern number 51. (a) and (c) are Cavity voltages. (b) and (d) are amplifier powers.



(a) (b)

Figure 5: Comparison of SP and FIFO patterns: (a) cavity voltage and (b) average amplifier power.

The initial cavity voltage $V_{cav,0}$ is 18.7 MV. As can be seen, without feed forward any deviation from this voltage would be treated as noise and the LLRF system will be triggered to react, which causes the amplifier power to fluctuate. The feed forward takes the beam loading into account, so it will not trigger the LLRF. Without feed forward, the cavity voltage needs to center around 18.7 MV.

FIFO vs SP Simulation results of the SP and FIFO patterns are given in Fig. 5. Feed forward is used in both. The SP patterns are superior as it has lower cavity voltage fluctuations $\sigma_{V_{cav}}$ and require much less amplifier power P_{amp}.

Pattern Dependence

We also observe the cavity voltage and amplifier power are pattern dependent in Fig. 5. We selected two patterns (number 1 and 51) plotted their V_{cav} and P_{amp} in Fig. 6. We used feed forward and SP patterns. Pattern number 51 is superior as it has lower cavity voltage fluctuations $\sigma_{V_{cav}}$ and requires less amplifier power P_{amp}. As can be seen, pattern number 1 has a bunch sequence of {123456} and thus has a 3-up-3-down beam loading pattern. Pattern number 51 has a bunch sequence of {142536} and thus has a 1-up-1-down beam loading pattern. Therefore, pattern 51 has lower cavity voltage fluctuation and it also required a little less power.

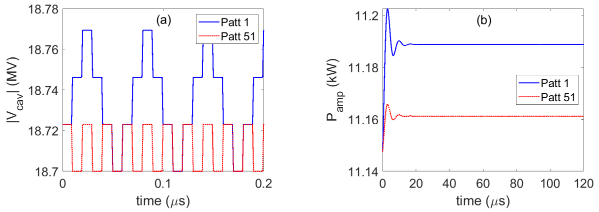


Figure 6: Comparison of pattern number 1 and 51. (a) and (c) are cavity voltages and (b) and (d) are average amplifier powers.

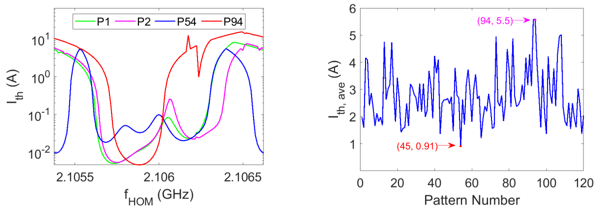


Figure 7: BBU frequency scan results. (a) I_{th} as a function of HOM frequency for different patterns. (b) $I_{th,ave}$ of 120 patterns.

BEAM BREAKUP INSTABILITIES

In our Beam Breakup Instabilities (BBU) studies, we observed beam loading pattern dependence of BBU threshold currents (I_{th}), as can be seen from Fig. 7. I_{th} is a quasi-periodic function of the frequency, so we have scanned 1 period around a High Order Mode (HOM) frequency of 2.106 GHz, as shown in the sub-figure (a). Then the averages of the I_{th} over the 1 period $I_{th,ave}$ for 120 beam loading patterns are given in the sub-figure (b). A significant difference (factor of 6) is observed between best (pattern# 45) and worst (pattern# 94) patterns.

CONCLUSION

The ERL filling and beam loading patterns have big impacts on the cavity voltage and RF power. Our simulations showed in ERLs cavity voltage fluctuation and amplifier power consumption can be lowered by using: (1) LLRF system with feed forward; and (2) best SP beam loading patterns. The BBU threshold current of the ERLs is also pattern dependent and one can increase the threshold current significantly by choosing the right patterns. Our studies have big implications for the design of future ERLs to lower cavity voltage fluctuations, amplifier power consumption, and increase the threshold current.

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