Monte Carlo simulations of energy lost due to random voltage spread in an XFEL RF unit

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Abstract

A computer simulation was written and used in order to estimate the energy lost due to voltage spread in the cavities affecting an XFEL RF unit. Two different approaches were applied to simulate the outcome of the cavities performance under specific initial conditions.

1 Introduction

The main target of XFEL is to produce X rays pulses extremely bright, ultrashort and with spatial coherence. These pulses will be used in multidisciplinary research experiments.

The heart of the XFEL complex is the L-band (1.3 GHz) electron linear accelerator with a nominal design energy of 17.5 GeV, operating at an accelerating gradient of 23.6 MV/m. It uses an advanced superconducting radio frequency (SRF) technology developed by the international TESLA Collaboration.[1, 2]

The European XFEL will use a series of 10MW klystrons to drive each one a unit of 32 SRF cavities[1]. Ideally all cavities would be run at the same voltage using the same RF microwave coupling factor, with the microwave power fed to each cavity being the same. In this ideal case, the waveguide distribution system from klystron to cavities divides the power equally between the 32 cavities. (see Figure 1)

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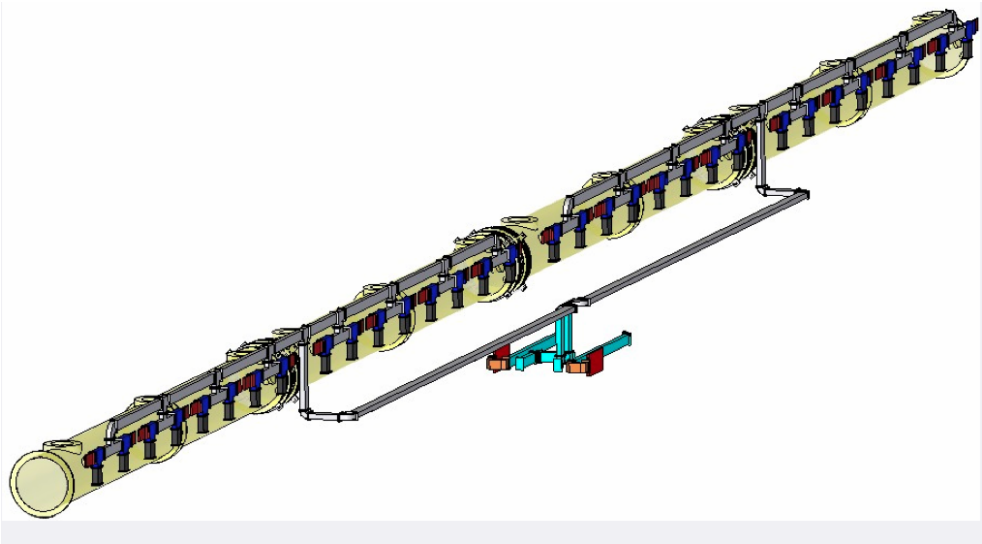

Figure 1: Picture of a XFEL RF unit powered by a 10MW klystron

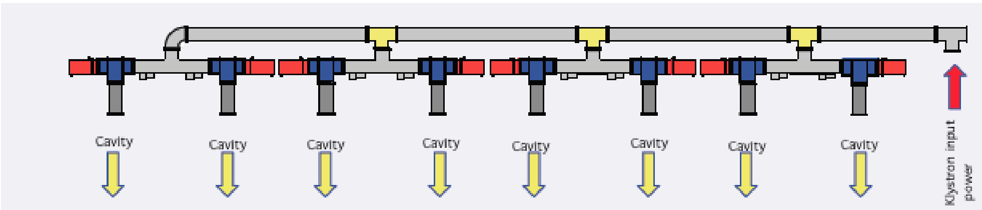

Figure 2: Section of a XFEL klystron wave-guide distribution for a RF unit (32 cavities)

Figure 2 shows the arrangement of the klystron wave-guide. In the picture the yellow connectors are the Symmetric Shunt Tee. These connectors allows us to change the distribution ratio of each cavity (it is only possible to change them during the installation). However, this wave-guide distribution has a fixed power distribution at the last ramification, so that the cavities have to be paired and the lowest value of the voltage has to be chosen.

The SRF cavities (see Figure 3) are hollow devices with axial symmetries, powered by RF (i.e. microwaves). It is a nine-cell resonator with a fundamental frequency of 1.3 GHz.[1]

Figure 3: Picture of a SRF cavity

There is a statistical spread in the maximum cavity performance due to fabrication factors. The ideal case of running all cavities with equal power would then limit the overall performance of the RF unit to the weakest performing cavity, and a significant loss in total achievable voltage would result.

The maximum accelerating voltage that the cavity reaches depends on the quench limit of that cavity. Since the maximum voltage is not the same for all the cavities, the power distribution system will be tailored to deliver a forward power to the individual cavities which matches their performance limits. Thus we can in principle achieve the maximum energy gain from the RF unit. Unfortunately this is compromised by beam loading.

The solution for the maximum performance is achieved by adjusting the forward power to the cavity (P_{for}), the fill time of the cavity (t_{fill}) and the cavity coupling, which we will discuss in terms of the external Q (Q_{ext}). The solution is unique for a given beam current I_b. In principle if we had control over all these parameters, we can match the system to any choice of beam current and cavity voltages for a given RF unit. However, the XFEL does not have adjustable power control on individual cavities: the power distribution ratios are fixed for the zero current case during installation and cannot be changed. Therefore, in general, when we accelerate the beam, we will loose a little gradient, the amount of which is a function of the beam current.

2 Methodology

During the t_{fill} the evolution of the voltage in the cavity is given by [3]

$$V_g(t) = V_g(1 - e^{-t/\tau}) \tag{1}$$

Where V_g is the klystron voltage and τ is the time constant of the charging/ discharging of the cavity.

At t=t$_{fill}$, once the voltage desired is reached, the constant current beam starts. The effects of the beam in the voltage are described by:

$$V_b(t) = -I_b R_{ext}(1 - e^{\frac{-(t-t_{fill})}{\tau}}) \tag{2}$$

where

$$R_{ext} = (\frac{r}{Q})Q_{ext} \tag{3}$$

and

- $\frac{r}{Q}$ is the characteristic impedance of the cavity (a constant for the cavities) and is equal to 1036 Ω
- Q_{ext} is the external Q, which is adjustable via a motor on the power coupler in the range of $1 - 1 \times 10^7$. In this study Q_{ext} was used with a value of 4.8×10^6.
- I_b is the beam current.

The cavity charges up like a capacitor when the forward power is applied. The time constant of the cavity is given by:

$$\tau = \frac{Q_{ext}}{\pi f_0} \tag{4}$$

where f_0 is the cavity frequency (1.3 GHz).

The necessary forward microwave power is given by

$$P_{for} = \frac{1}{4}\frac{V_g^2}{R_{ext}} \tag{5}$$

The remaining parameter we need to consider is the fill time t_{fill}. This is the time it takes at the beginning of the RF pulse to charge up the cavity to the required voltage V_a (accelerating voltage) at the point when the beam pulse (beam current) arrives. The fill time can be calculated as:

$$t_{fill} = -ln\left(1 - \frac{V_a}{V_g}\right)\frac{Q_{ext}}{\pi f_0} \tag{6}$$

A consequence of driving 32 cavities with a single RF source (10MW klystron) is that the fill time must be the same for all cavities, which further constrains the problem.

If the forward power is the same as before t_{fill}, then the voltage the cavity is given by

$$V_a(t) = V_g(t) + V_b(t) = V_g(1 - e^{-t/\tau}) - I_b R_{ext}(1 - e^{\frac{-(t-t_{fill})}{\tau}}) \tag{7}$$

The forward power can be different during the beam pulse compared to the fill time (no beam). If we call the ratio of fill time power to beam pulse power r, then equation 7 can be written as

$$V_a(t) = \sqrt{4P_{for}R_{ext}}((1-\sqrt{r})e^{\frac{-(t-t_{fill})}{\tau}} + \sqrt{r} - e^{-\frac{t}{\tau}}) - I_b R_{ext}(1 - e^{\frac{-(t-t_{fill})}{\tau}}) \qquad (8)$$

for t $> t_{fill}$

Now that we have understood the single cavity behavior, we will study the time evolution of the voltage in a XFEL RF klystron Unit. In this study we assumed an individual cavity performance variation of ±20% around 25 MV. Therefore using an algorithm that gives pseudo-random numbers we are able to make a distribution of the cavities in a RF unit (32 cavities for the XFEL experiment).Then we pair them (see Figure 4). The weakest cavity in each pair will define the forward power for that pair. After pairing the cavities, we normalize each value, with the purpose of having the mean of this distribution fixed to 25 MV.

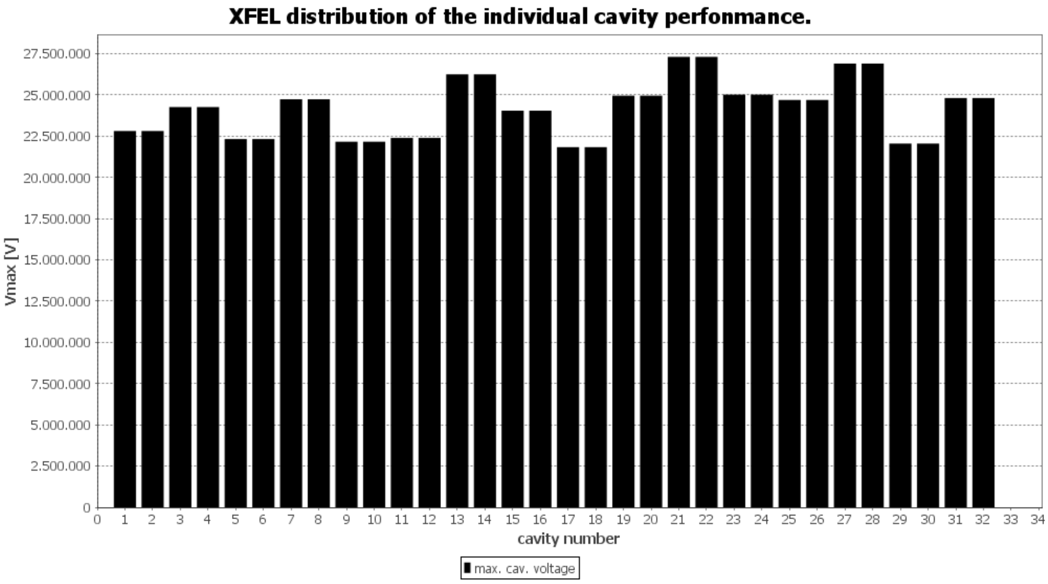

Figure 4: Simulated example of voltage spread of a single RF unit

The next step is to calculate the required forward power (P_{for}) to each of these pairs running at the operational gradient. For XFEL, the value of t_{fill} is of 820 μs [1]. First, the forward power required for each cavity to achieve its voltage in the required t_{fill} has to be calculated. The first step for this is to calculate V_g from equation 1 and its forward power from equation 4. The klystron power P_k is the sum of each cavity forward power.

In this report a constant and equal phase for all cavities is assumed, therefore the vector sum only involves the amplitudes of the voltages of each cavity. The parameter r has to be modified in a such way that the vector sum remains flat during all the beam loading time, as seen in Figure 5. In this study we use a total pulse length of 1450 μs.

Then we proceed to calculate the vector sum for each unit, using equation 8. The vector sum feedback will adjust both, P and r, to achieve a constant voltage across the beam pulse.

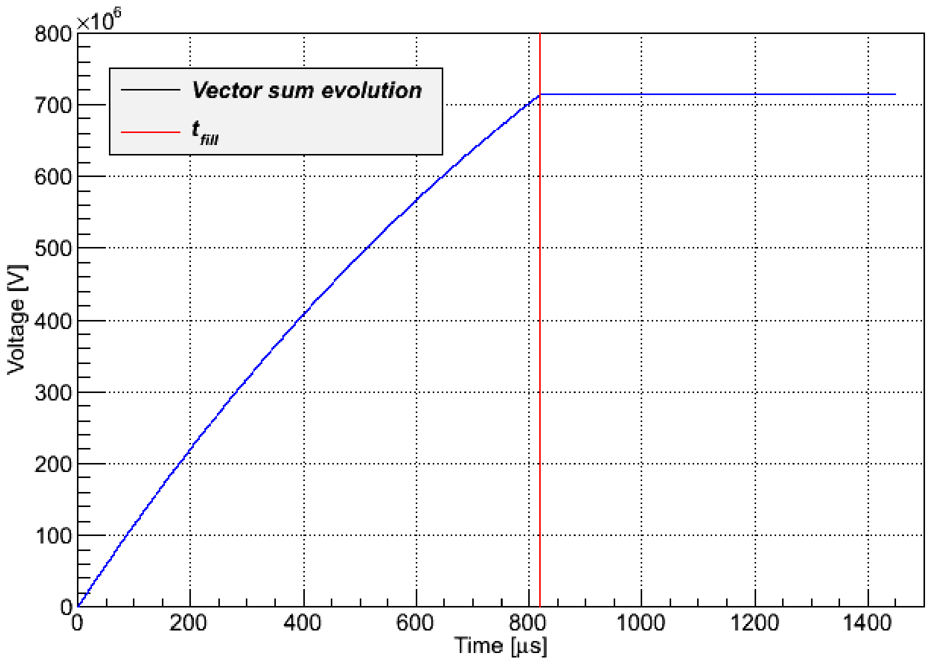

Figure 5: Evolution of the vector sum along the length of the beam pulse

From Figures 5 and 6 we can see that, although we have arranged for the vector sum to be flat at the required value; the individual cavities all have different slopes but the average is flat.

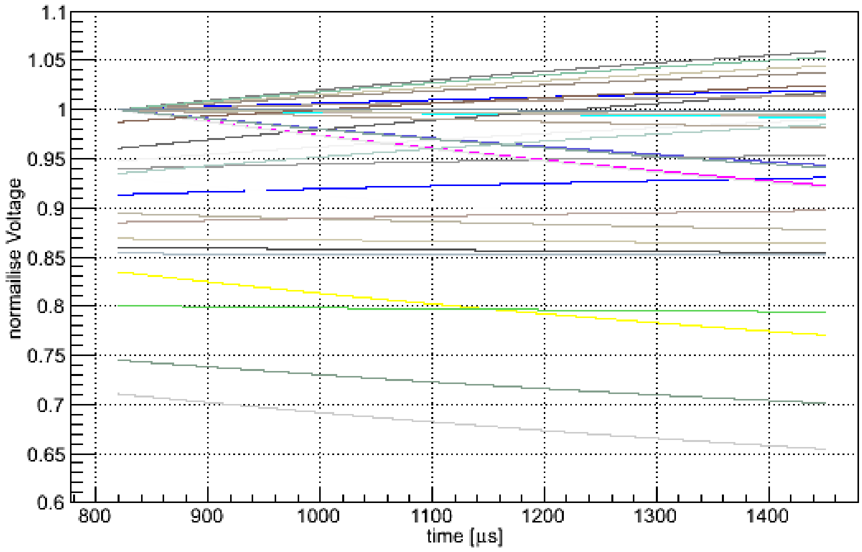

Figure 6: Accelerating voltage of each cavity divided by its maximum determined value in order to measure its quenching

So we proceed to normalise the individual cavity voltages to their quench limits as shown in Figure 6. We know that a cavity quenched when, as shown in this graph, it crosses the value of 1 in the y axis. We can see that several of the cavities have quenched during the beam time. To avoid the cavity to exceed its maximum voltage value we can proceed in two different ways:

- Reducing the total value of the power generated by the klystron.
- Reducing the value of the accelerating voltage of the pair that is quenching.

(see Appendix)

2.1 Total klystron power reduction

With this method, first we verify which cavity quenched then, for each cavity that quenched we reduce the total klystron power until no cavity quenches.

After the power of the klystron (P_k) is reduced the parameters of the equation 8 are calculated again, in order to maintain the vector sum constant for a given klystron power.

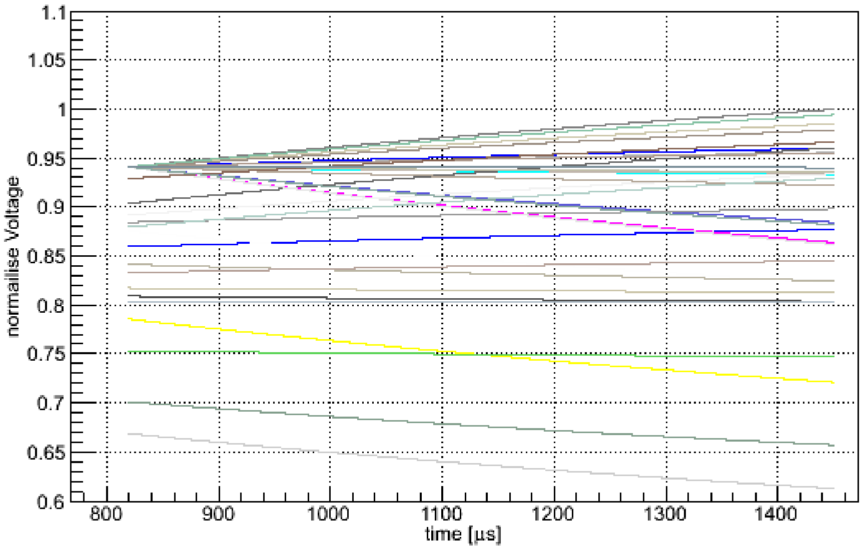

Figure 7: Voltage of each cavity divided by its maximum value in a reduced klystron power, so the quench of the cavities is avoided.

As we can see in Figure 7 the maximum value of every cavity is never exceeded therefore we ensure that each cavity runs at its highest possible accelerating voltage without any cavity quenching.

2.2 Voltage reduction on paired cavities

With this method, first we verify which cavity quenched. Then, to each cavity that quenched we reduce the initial voltage of that cavity and its pair. The klystron forward power is also reduced (and therefore the vector sum), but only by the amount due the pair that is being adjusted. All other cavities stay at constant power. This is the difference to the first method.

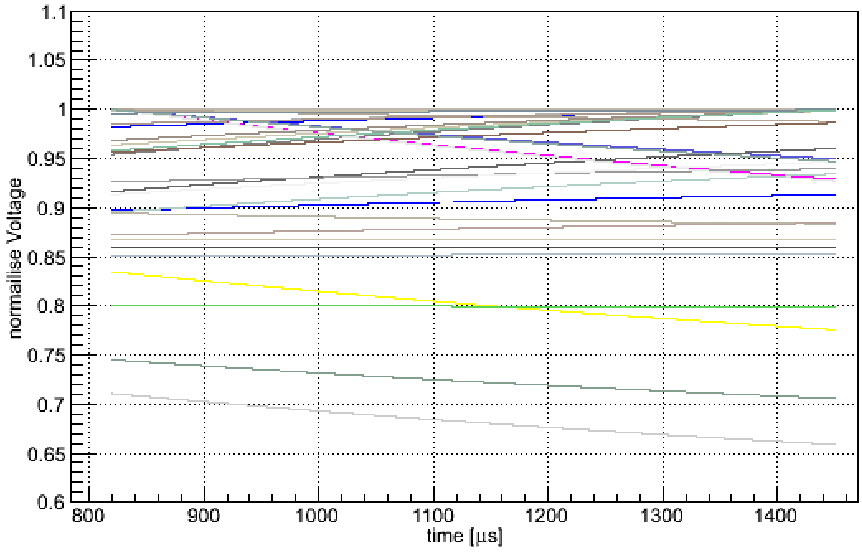

Figure 8: Voltage of each cavity divided by its maximum value. The voltage of individual cavity pairs is reduced by adjustment of the power distribution ratio, in order to avoid quenching.

3 Analysis and results

This simulations have been repeated for different values of the current. From 0 mA to 5 mA. A Monte-Carlo study has been made for each value of the current; for a given value of the current the simulation was made with 100,000 RF units with random voltages taken from a flat distribution (average 25 MV/m with a ±20% spread).

The following graph (Figure 9) shows the distribution for the two distinct approaches that were studied. The error bars represent 1 standard deviation.

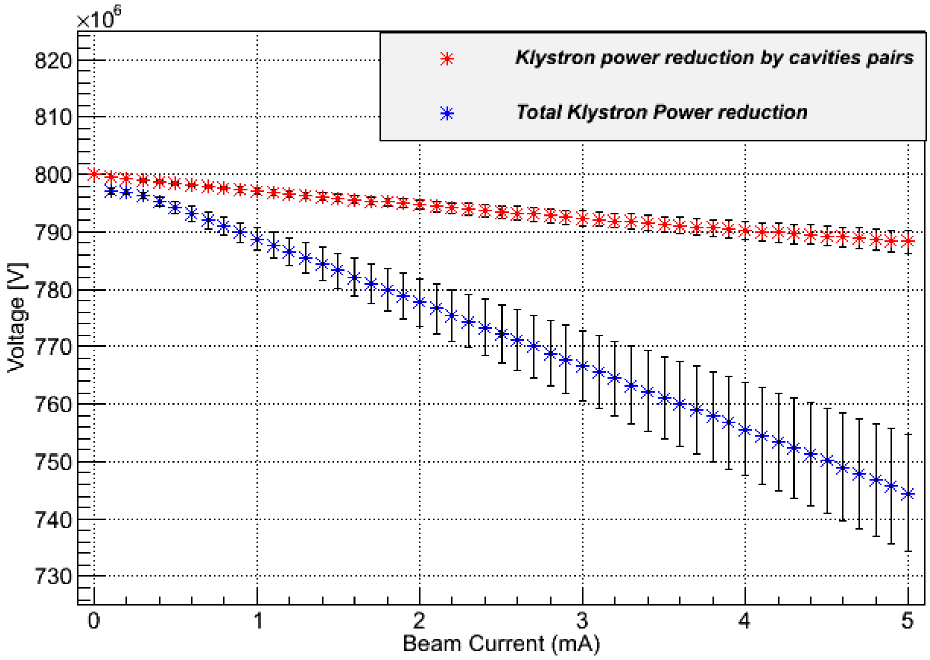

Figure 9: Distribution of the total voltage per unit(32 SRF cavities) vs the beam current (in red) when the initial voltage of the cavities is reduced to avoid quenching from the cavities and (in blue) when the klystron power is reduced to avoid quenching from the cavities

We can see that the vector sum voltage reduction distribution is different for each case. For the case that we reduced the initial voltage of the cavity we can see that the vector sum voltage reduction is of 1.5% at 5 mA but, it is physically more complicated to realize because the initial power distribution ratios cannot be modified after initial installation. In the case were the klystron power is reduced the vector sum voltage reduction is of 7% and this case is easier to achieve because the klystron power can be changed remotely during operation.

4 Conclusion

Depending of which method is used the vector sum voltage reduction due to the random voltage spread is different. In this study we used a fixed Q_{ext}. It means that these results are valid assuming a constant and equal Q_{ext}. Our simulations show that reducing the initial accelerating voltage of each cavity causes the less vector sum voltage reduction. Comparing both efficiencies it shows that the first method (reducing the total klystron power) loses more than 4 times more voltage reduction than the other method. But this method (reducing the initial acceleration voltage of each cavity) is more difficult to implement.

The method where the total power from the klystron is reduced,it typically looses 7% of its initial energy due to the assumed ± 20% voltage spread.

References

[1] M.Atarelli et al. *"XFEL: The European X-Ray Free-Electron Laser: Technical design report"*, DESY Report DESY 2006-097, July 2006.

[2] V. Vogel, L.Butkowski, et al. *Results of Testing of multi-beam klystrons for the european XFEL*,Proceedings of LINAC2012, Tel-Aviv, Israel, 2012.

[3] Thomas P. Wangler *"RF Linear Accelerators"* 2nd. Edition. WILEY-VCH, 2008.

Appendix

The two computational algorithms for the different approaches are shown ahead

Method1 : Total klystron power reduction

We define a vector called Quench with 32 parameters because of the length of the RF unit (32 cavities in this case). Where, for a single cavity, the value of the accelerating voltage at each given time is divided by its cavity performance value. And it is stored as a parameter of the Quench vector. (See Figure 6)

Then a while loop is made in the following way

{

while (a value inside the Quench vector is bigger than 1) Reduce the value of the Klystron Power by 0.1% .

Then, we calculate the new values for $V_g(t)$ using equation 1 and P_{for} using equation 5. And then, we recalculate value of r is calculated using the new value of the vector sum obtained from each cavity using equation 8 and adding them.

The value of $V_a(t)$ is divided by the value of the cavity performance (as presented in Figure 4) ands then stored in the Quench vector.

$$Quench = \begin{pmatrix} \frac{V_{a,1}(t)}{V_g} \\ \frac{V_{a,2}(t)}{V_g} \\ \vdots \\ \frac{V_{a,32}(t)}{V_g} \end{pmatrix}$$

} End of the while loop.

Therefore, if a value in the Quench vector is bigger than 1 the while loop will cycle until all cavities haven't exceed their maximum performance value.

Method2 : Voltage reduction on paired cavities

We define a vector called Quench as the same as in the previous method.

Then a while loop is made in the following way

{

while (a value inside the Quench vector is bigger than 1)

Reduce the value of the voltage of the pair of each cavity that exceeded its maximum value. Reduce it by 0.1% its value.

Then, we calculate the new values for $V_g(t)$ using equation 1 and P_{for} using equation 5. And then, we recalculate value of r is calculated using the new value of the vector sum obtained from each cavity using equation 8 and adding them.

The value of $V_a(t)$ is divided by the value of the cavity performance (as presented in Figure 4) ands then stored in the Quench vector.

$$Quench = \begin{pmatrix} \frac{V_{a,1}(t)}{V_g} \\ \frac{V_{a,2}(t)}{V_g} \\ \vdots \\ \frac{V_{a,32}(t)}{V_g} \end{pmatrix}$$

} End of the while loop.

Therefore, if a value in the Quench vector is bigger than 1 the while loop will cycle until all cavities haven't exceed their maximum performance value.