Coupling adjustment considerations

Julien Branlard, Uros Mavric, Justin Keung*, Brian Chase,
Fermilab, *U-Penn

A- All cavities are at resonance

Let's consider the simple case of two cavities, one with a nominal gradient of V_0=33.5MV/m and a second reaching a lower gradient $V = V_0(1-d)$ where d ranges from 0 to 20%. (cf. C. Nantista & C.Adolphsen)

The coupling adjustments to ensure a flat top in "beam-on" conditions can be obtained by solving for Q_L in the following equation:

$$\frac{V}{V_0} = \frac{Q_L}{Q_{L0}}\left(2^{\frac{Q_{L0}}{Q_L}} - 1\right)$$

where Q_{L0} is the nominal cavity loaded Q. The corresponding klystron power can then be derived using the following equation:

$$\frac{P_k}{P_{k0}} = \frac{Q_L}{Q_{L0}} 4^{\left(\frac{Q_{L0}}{Q_L}-1\right)}$$

where P_{k0} is the klystron power corresponding to the nominal cavity. The plot of Fig.1 illustrates this by showing the cavity voltages for 5 values of d . The nominal cavity is shown in red, while the lower gradient cavity is shown in blue.

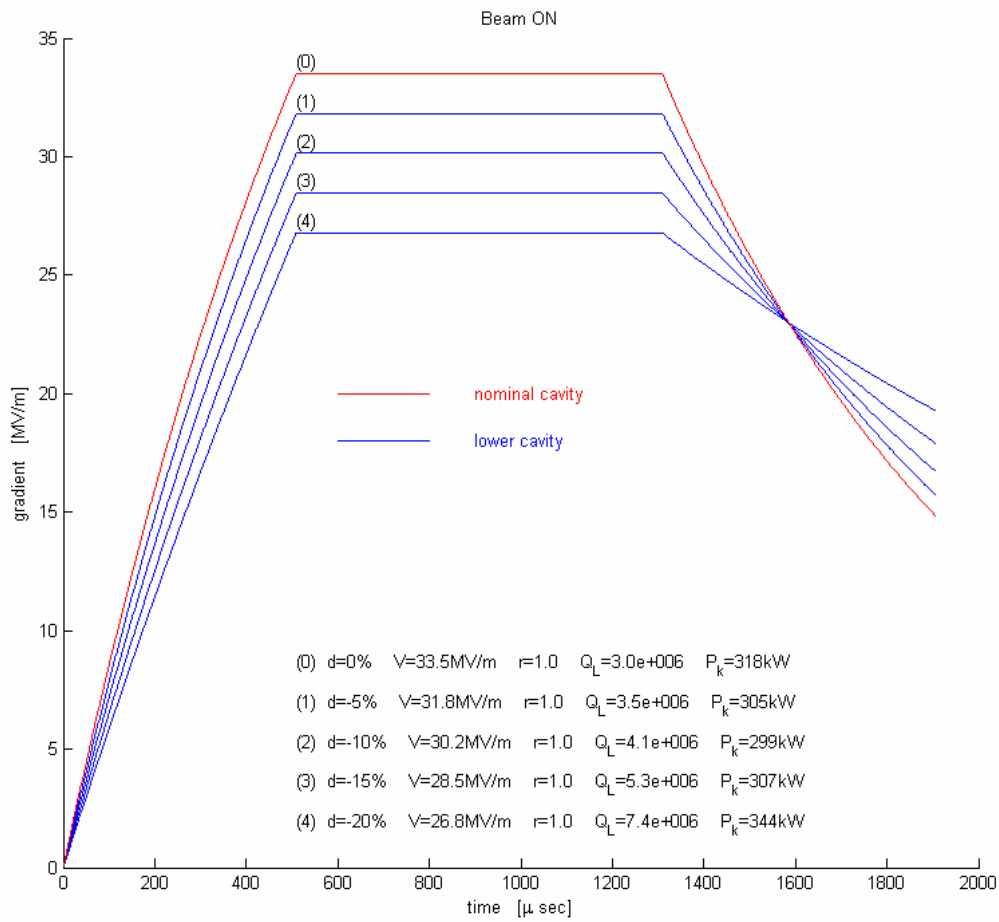
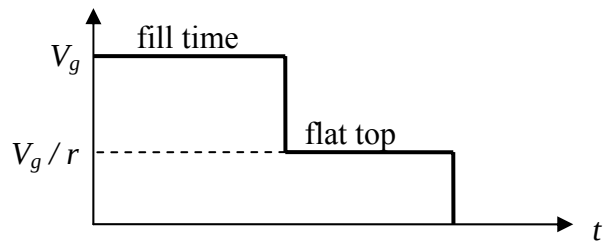


Figure 1: coupling and power adjustments for five different cavity gradients

The parameter r corresponds to the ratio by which the generator voltage is dropped during the flat top, as illustrated below:



When $r = 1$, the klystron power remains unchanged during the flat top.

As can be seen in Fig.1, as the gradient is lowered, the Q_L is increased. However, the klystron power first decreases, passes through a minimum and start to increase again. This non-monotonic behavior of the power can be better understood by looking at a power-vs-gradient curve, shown in Fig.2.

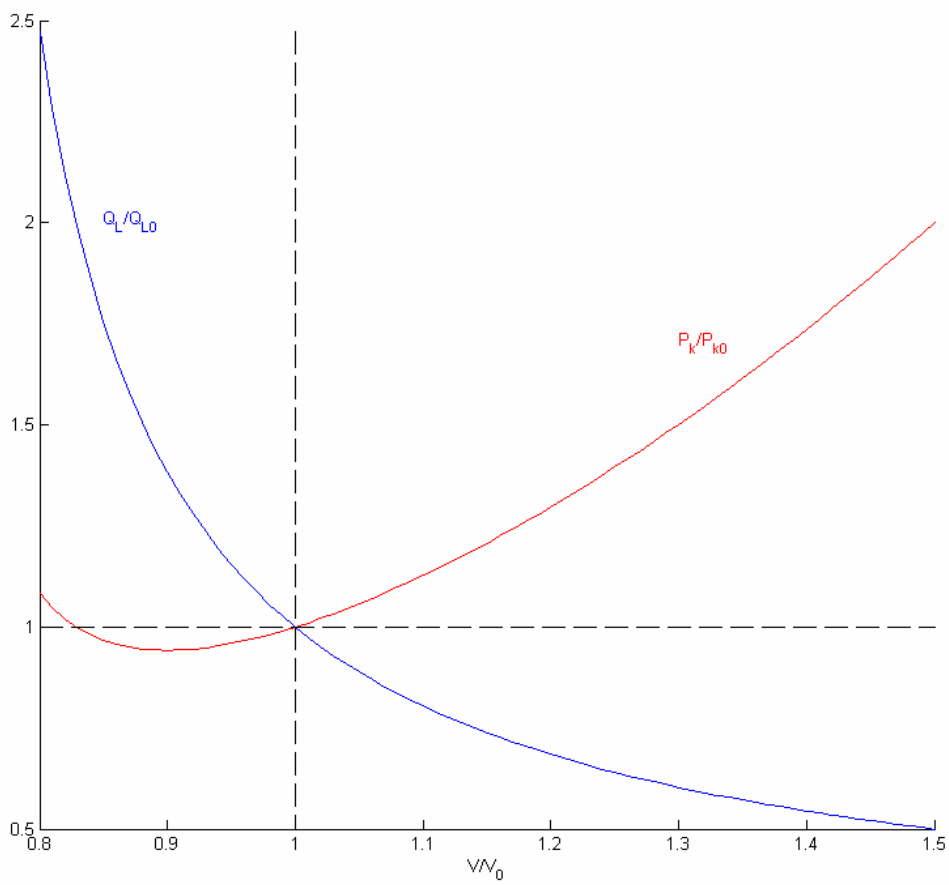


Figure 2: coupling and power variations as a function of gradient

Indeed, Q_L is a decreasing function of the gradient, while the power goes through a minimum around d=10%

In the "no-beam" condition, the RF voltage is dropped by a ratio *r* during the flat top so that the vector sum of all gradients remains flat. This does not require individual cavity gradients to be flat, and actually, it will not be the case if the cavities have different nominal gradient. In the general case of *N* cavities, this ratio can be obtained by the following equation:

$$r = \frac{1}{1 - \frac{N}{\sum_{i=1}^{N} 2^{\frac{Q_{L0}}{Q_{Li}}}}}$$

where Q_{L0} is the nominal loaded Q and the Q_{Li} are given for each cavity. This ratio is only a function of the loaded Q's, and in the special case where all gradients are nominal, all $Q_{Li} = Q_{L0}$ and *r* becomes 2, as expected.

The "no-beam" case is illustrated in Fig.3. The blue traces correspond to the lower cavity for two different values of *d* (3% and 8%). The black trace corresponds to the gradient sum of the nominal and the lower cavity.

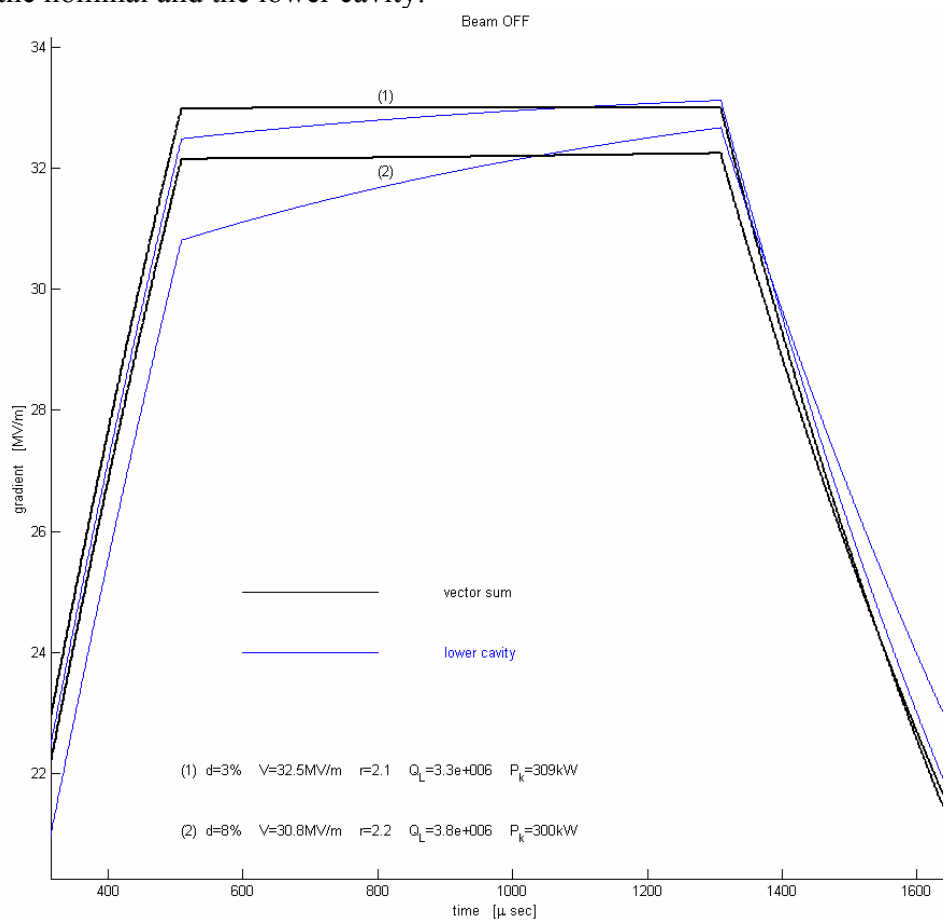


Figure 3: the forward power is dropped to maintain a flat top in "no-beam" condition

The ratios are being increased (i.e. the forward power is increasingly dropped during the flat top) as the gradient of the lower cavity decreases. As can be seen, adjusting the ratio *r* ensures that the vector sum remains flat during the flat top (black curves). However, this is not the case for individual cavities, as can be seen in the case of the lower cavity (blue trace). This behavior is not desirable because the gradient of the

lower cavity now exceeds its quench limit. Several approaches can be considered to address this issue.

a) Adjusting the generator voltage ratio to flatten the lowest cavity gradient

While not a solution due to operational concerns, for completeness, we explore loosening the requirement on the flatness of the vector sum. One can calculate the ratio by which to adjust the flat top voltage drop so that the gradient of this particular cavity won't exceed its nominal value. As a result, the gradient sum will no longer be flat, but this guarantees that no cavities will exceed its quenching gradient.

For a given cavity, the "optimal" ratio (i.e. to maintain a flat top for an individual cavity) is given below:

$$r = \frac{1}{1 - \frac{1}{2^{\frac{Q_{L0}}{Q_L}}}}$$

This is illustrated in Figure 4. In this figure, the flat top voltage drop is adjusted so that the lower cavity gradient won't exceed its nominal value. Notice how the ratios calculated here are larger than in Fig.3. Consequently the gradient sum, shown in black, is no longer flat

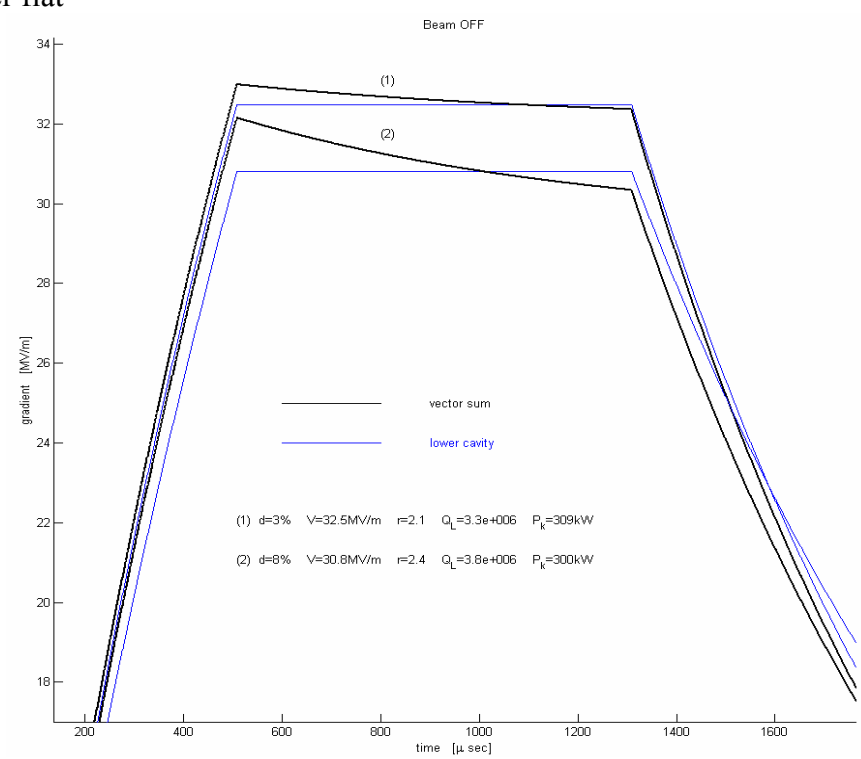


Figure 4: the generator voltage ratio is adjusted to ensure the lower cavity does not quench

In the case of *N* cavities, the lowest one will dictate which ratio to drop the voltage by, in no-beam or low-beam conditions.

b) Lowering the set point of the cavity with the lowest gradient

A second attempt consists of lowering the cavity set point. As shown in this section, the quenching limit is always exceeded in no-beam conditions with a full pulse length.

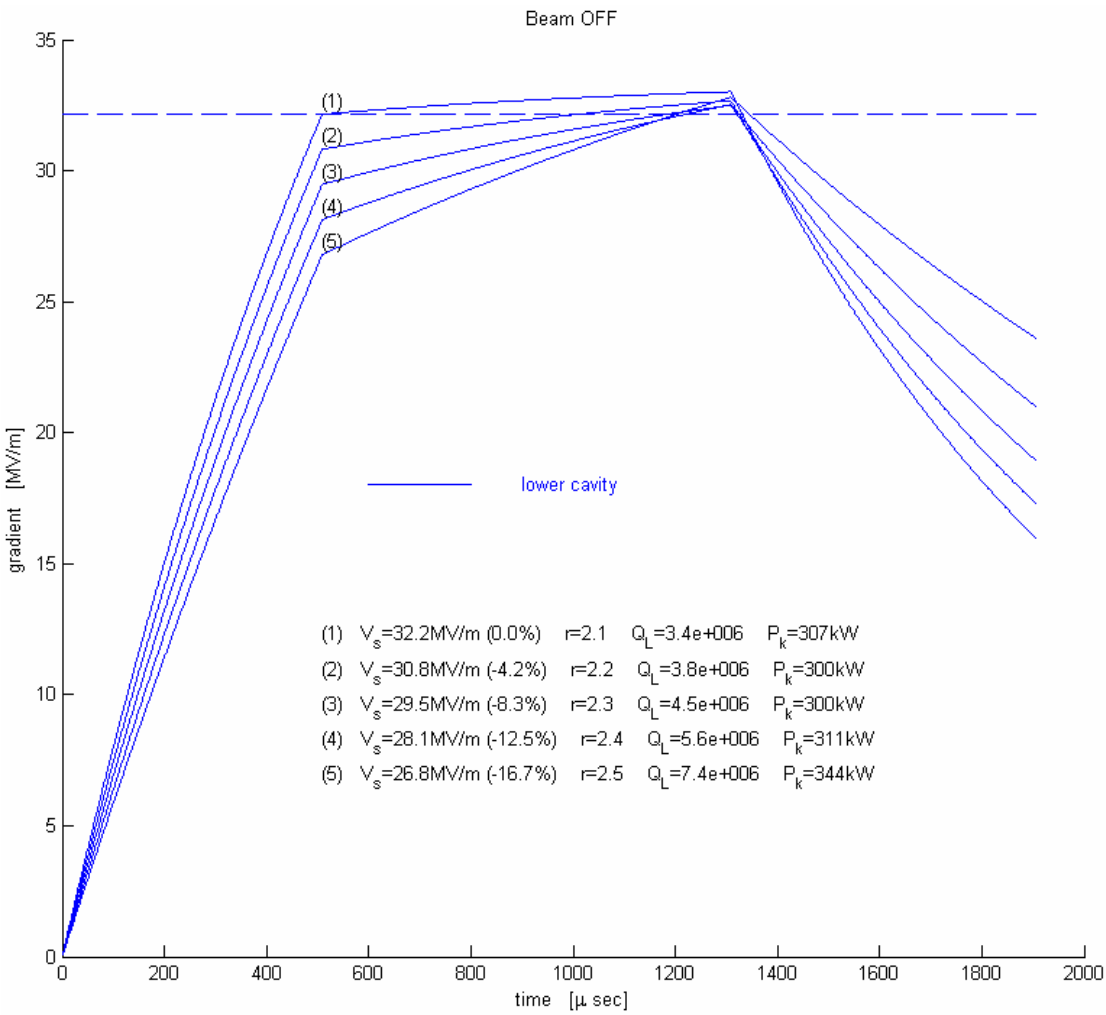


Figure 5: attempt to lower the set point to avoid quenching the cavity

Let's consider the case of a cavity that can only reach a maximum gradient 4% below the nominal gradient of 33.5 MV/m (i.e. 33.5 x 96 % = 32.2 MV/m). This quenching gradient is shown in dashed line in Fig.5. By lowering the set point of the cavity, one can hope that the cavity gradient won't exceed its quenching limit. However, in order to maintain the beam operation conditions described earlier, the coupling and the power are adjusted accordingly so that when the beam is on, the cavity gradient is flat. This is illustrated in Fig.5, where the set point amplitude is lowered from its maximum value (32.2 MV/m) to about 17% lower (26.8 MV/m). Looking closer on the last gradient values before the RF is turned off, one can see that as the set point amplitude is decreased, the slope of the gradient increases (following the Q_L adjustments), as illustrated in Fig.6.

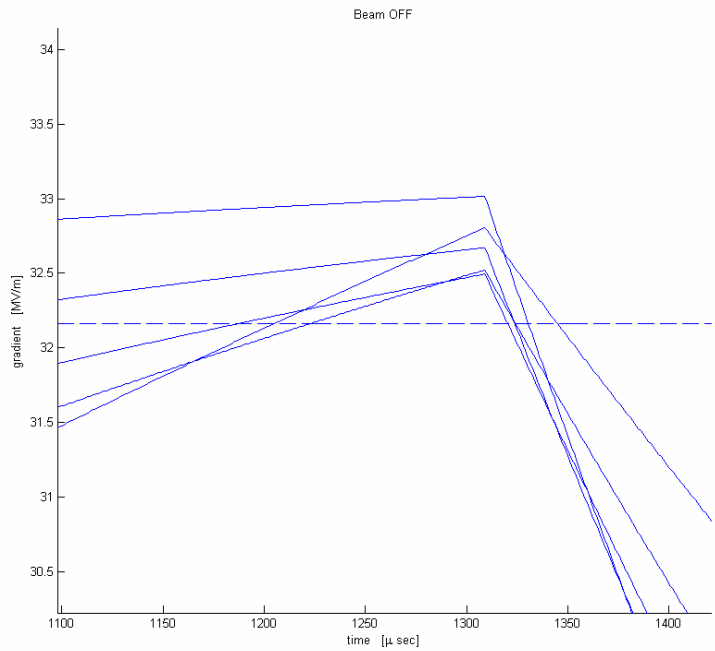


Figure 6: close up on the final values of the lower gradient cavity at the end of the RF pulse

The voltage drop ratio is being adjusted so that the gradient sum remains flat, regardless of the behavior of individual cavities.

This example illustrates a situation where a cavity with a lower nominal gradient cannot be prevented from quenching by lowering its set point (if one requires the vector sum to be flat).

c) Adjusting the coupling to annul the reflected power of the lower cavity

Another approach to the problem of under coupled cavities quenching in low beam condition is to adjust the coupling of every cavity so that the lowest cavity ($V_{\min}$) will have no reflected power.

For this to happen, several parameters need to be adjusted:

1) The coupling of all cavities is changed using the same coupling formula, except that the coupling of the lowest cavity $Q_{L\min}$ is now used as reference:

nominal case: $\frac{V}{V_0} = \frac{Q_L}{Q_{L0}}\left(2^{\frac{Q_{L0}}{Q_L}} - 1\right)$ lowest cavity case: $\frac{V}{V_{\min}} = \frac{Q_L}{Q_{L\min}}\left(2^{\frac{Q_{L0}}{Q_L}} - 1\right)$

2) The klystron power distribution is changed using the same power formula except that the power of the lowest cavity $P_{k\min}$ is now used as reference:

nominal case: $\frac{P_k}{P_{k0}} = \frac{Q_L}{Q_{L0}} 4^{\left(\frac{Q_{L0}}{Q_L} - 1\right)}$ lowest cavity case: $\frac{P_k}{P_{k\min}} = \frac{Q_L}{Q_{L\min}} 4^{\left(\frac{Q_{L\min}}{Q_L} - 1\right)}$

3) The fill up time is changed to match the lowest cavity rise time:

nominal case: $t_F = \frac{2Q_{L0}}{\omega_0}\ln 2$ lowest cavity case: $t_F = \frac{2Q_{L\min}}{\omega_0}\ln 2$

If we don't adjust the filling time, the lower cavities will overshoot.

The following plots have been obtained with 24 cavities, where there maximum gradient are normally distributed around 33.5 MV/m with a standard deviation of $\sigma = 5$. All the couplings are adjusted with respect to the lowest gradient cavity, so that the reflected power of the lowest cavity is null.

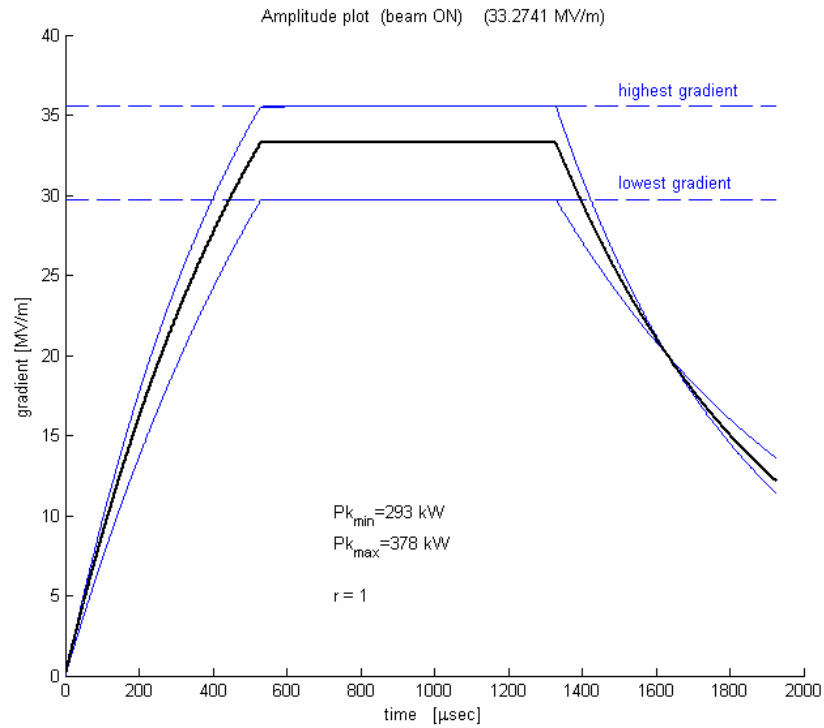


Figure 7: Coupling adjusted to annul the reflected power of the lowest cavity.

The highest and the lowest gradients are indicated in blue, the vector sum in black. The corresponding power plot is shown below, indicated the forward power, the reflected power, the beam power and the time derivative of the cavity stored energy. For clarity, only the case of the lowest gradient cavity is shown.

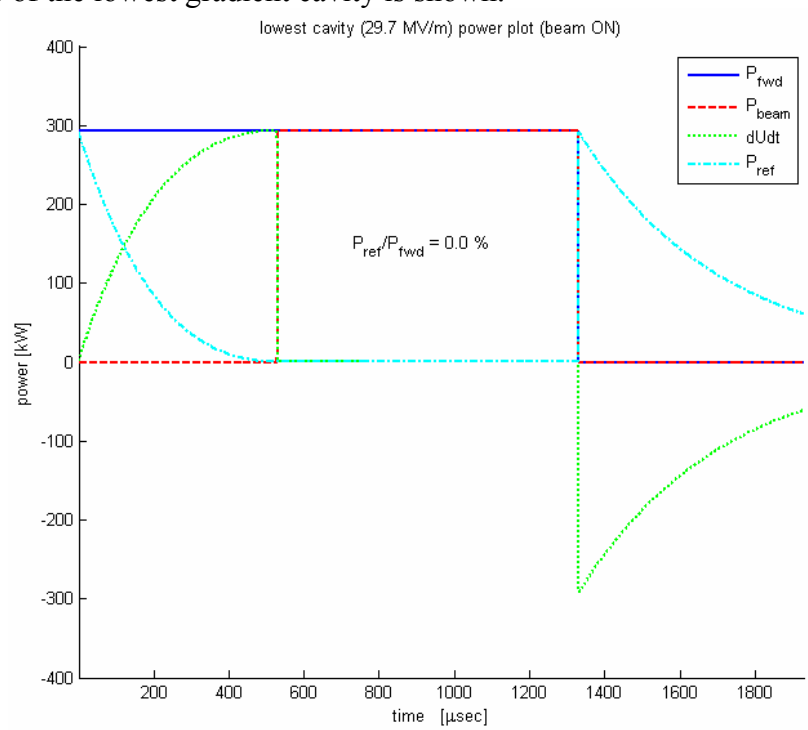


Figure 8: power plot for the lowest gradient cavity

As can be seen, the reflected power of the worse cavity is 0 when the beam is on, as expected.

The equivalent gradient and power plots when the beam is turned off and the coupling settings are maintained are shown below.

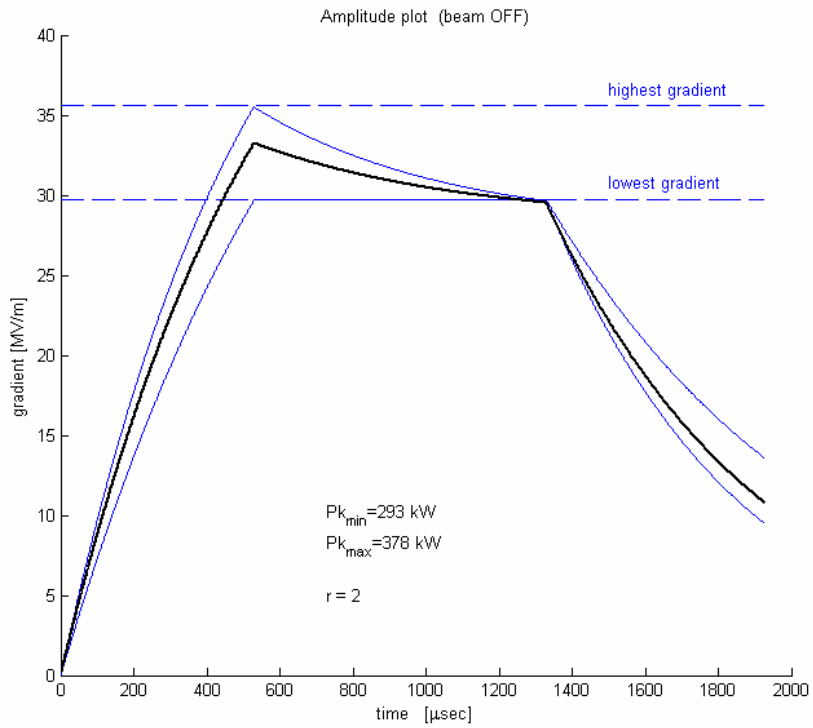


Figure 9: Gradient plot with no beam, when the coupling is adjusted to annul the reflected power of the cavity with the lowest gradient

Note that in this case, the ratio by which to drop the generator voltage during the flat top is 2. This agrees with the fact that the power and the coupling are referenced to the case of the lowest gradient. Obviously, the vector sum cannot be flat in this case.

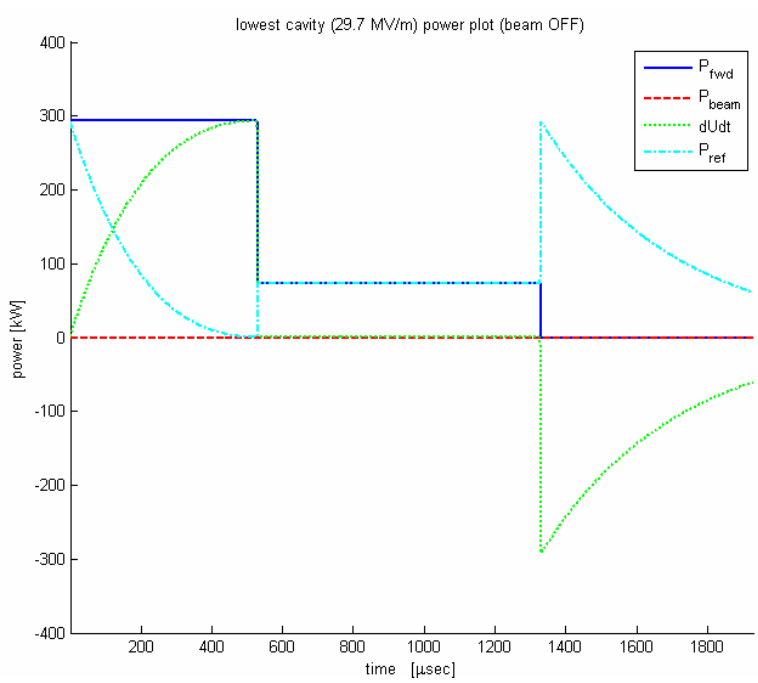


Figure 10: lowest cavity power plot, when beam is off.

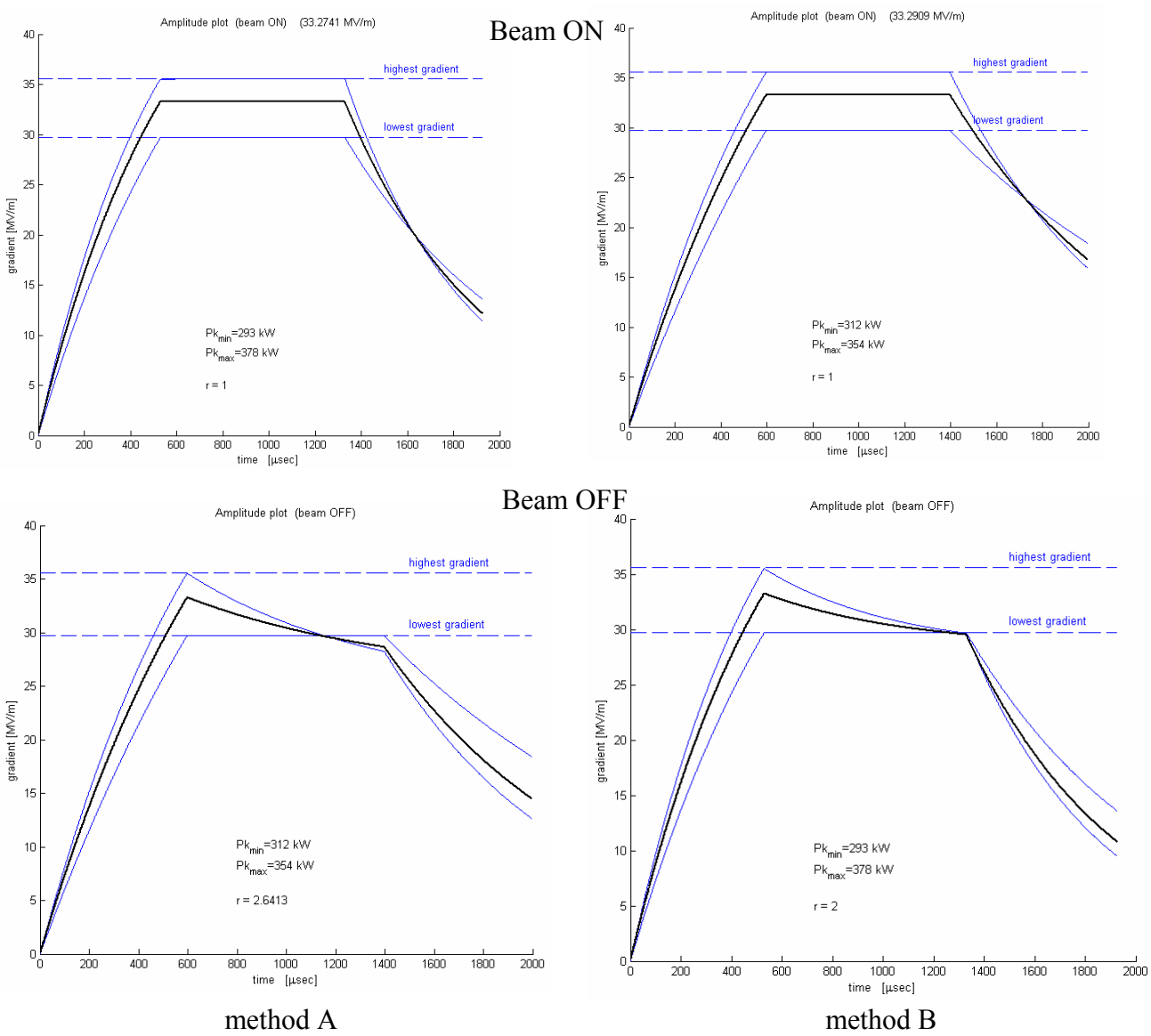
Note that on the power plot, the reflected power is perfectly matched with the forward power. This agrees with the fact that the cavity with the lowest gradient is now the reference cavity.

Conclusion:

This approach prevents any cavity from quenching in case of low or no beam. However, the vector sum cannot be maintained flat in the no-beam case. If we compare this method (method B) to that which consists of changing the ratio *r* to keep the worse cavity flat during the flat top (method A), two points can be made:

1) When the beam is on, method A yields a slightly higher vector sum than method B (33.29 MV/m instead of 33.27 MV/m)
2) When the beam is off, method A yields a worse droop in the vector sum than method B

These two points are illustrated in the figures below



method A method B

Figure 11: comparison of methods A and B (left and right) with and without beam (top and bottom)

B- Detuning the lower cavity

In the following section, the impact of detuning the lower cavity on its peak gradient is investigated. The simulations are obtained using Justin's Keung Penn Virtual Cavity (PVC) simulator (http://einstein.hep.upenn.edu/~keungj/simulation.html).

1) Initial conditions: no feed back, no beam

We consider a total of 8 cavities: 7 running at 33.5 MV/m and 1 cavity with a quenching limit of 31.8MV/m (5% below the nominal value) shown in red. The vector sum is shown in black.

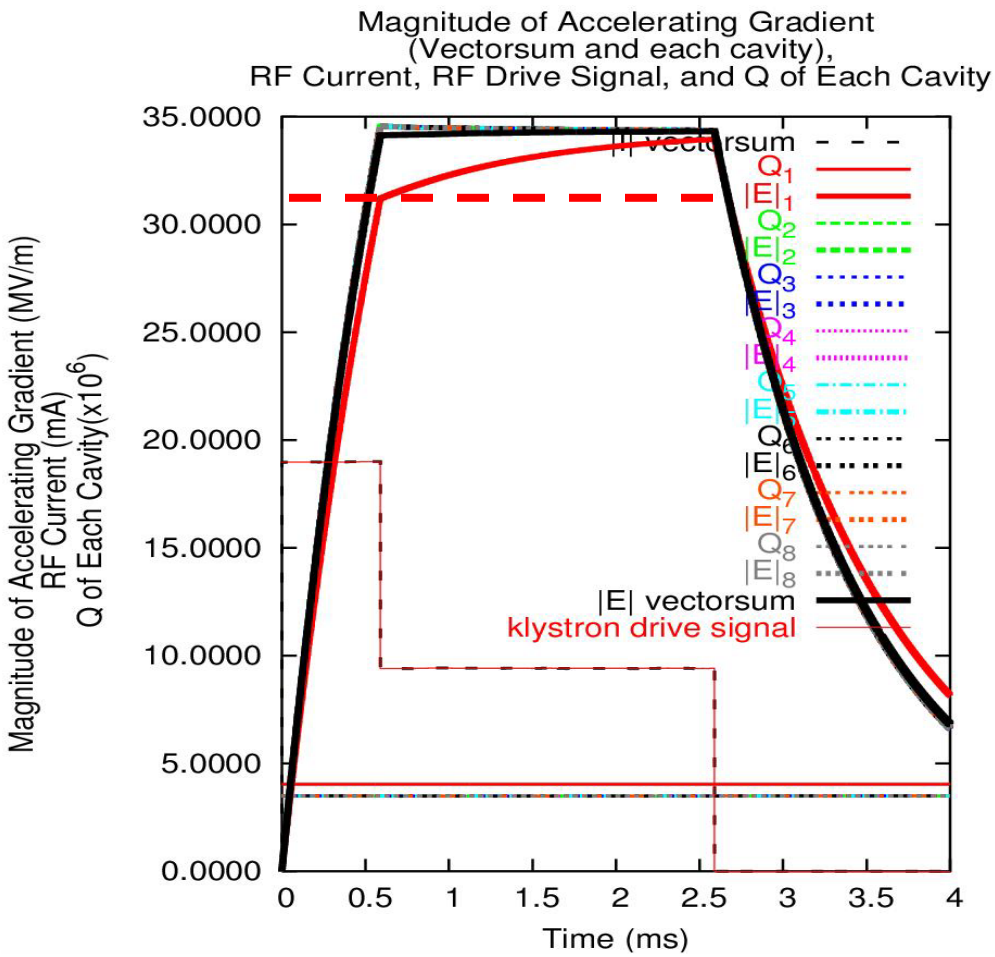


Figure 12: PVC simulation of 8 cavities, 1 of which only achieves a gradient 5% below the nominal value of the other cavities.

The generator voltage is dropped during the flat top to maintain a flat vector sum. The quenching limit of the "red" cavity is indicated in dashed line. In this situation, the lower cavity would quench in the absence of beam, as explained in section A.

2) Detuning the "bad" cavity yields a lower peak value

By adding some detuning in the simulation, the cavity voltage droops at the end of the RF pulse. This is illustrated in the figure below.

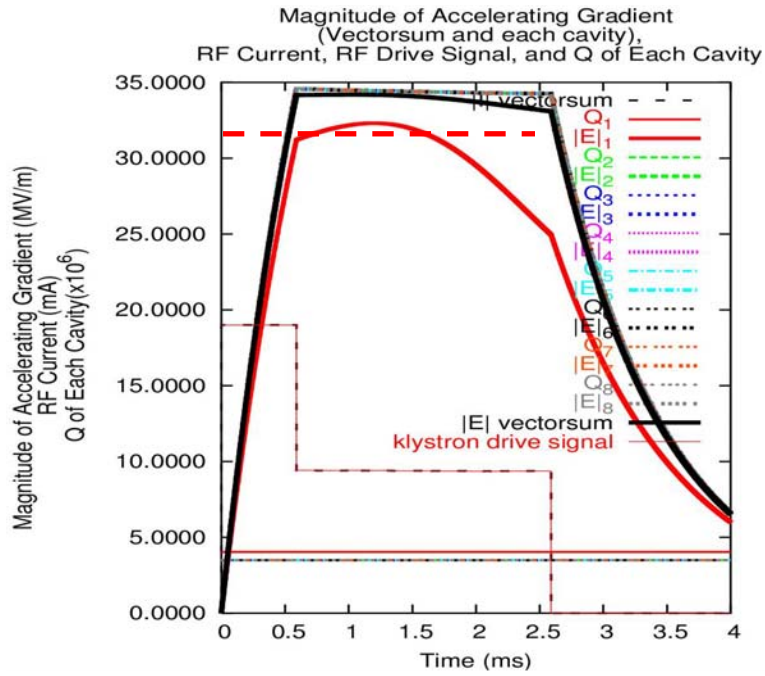


Figure 13: with detuning, the peak gradient droops at the end of the flat top

Besides detuning the lower cavity (red) all other settings (Q_L, P_k, r) have been kept constant with respect to the previous simulation. The observed drooping for the lower cavity results in a drooping (to a lesser extend) of the vector sum.

3) If we lower the set point for the "bad" cavity, we can prevent the bad cavity from quenching (although Q_L has been adjusted to maintain flat top with beam)

As explained in section A, in absence of detuning, lowering the set point does not prevent the lower cavity from quenching, because the benefits of running at a lower gradient are voided by the coupling adjustments, necessary for running with beam. However, detuning the cavity can balance the effect of the steeper slope due to coupling adjustments and prevent the "bad" cavity from quenching, as shown in Fig. 9.

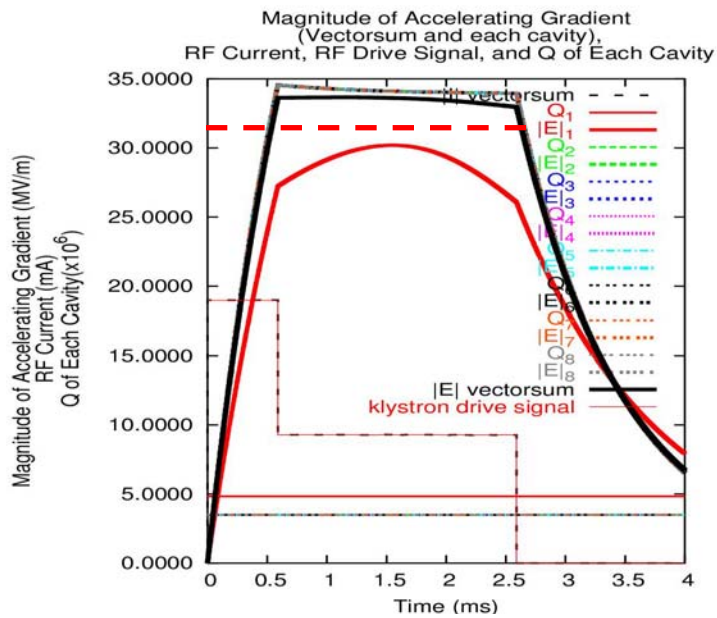


Figure 14: running the "bad" cavity at a lower set point and detuning it can prevent it from quenching

4) Finally, with amplitude feedback (G=100), we can adjust the klystron power to maintain a flat vector sum during the flat top

Now the drooping of the vector sum, due to the detuning of the bad cavity can be addressed by running in feedback mode, as illustrated in Fig. 10.

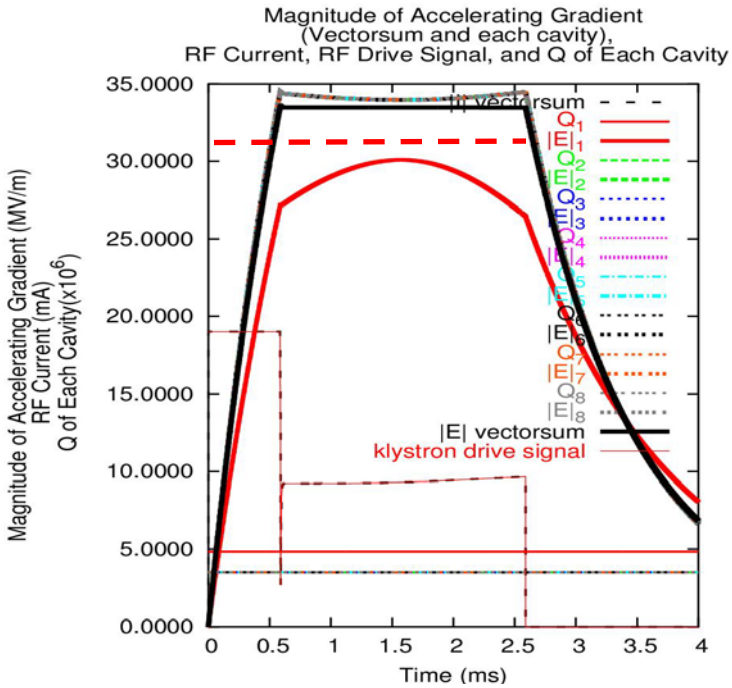


Figure 15: adding feedback can address the drooping induced by the cavity detuning

Conclusions:

For a distribution of cavity gradients close to their quenching limit:

- we can adjust each cavity RF distribution power and Q_L so that all cavities will be flat in "beam-on" conditions
- there is no solution that will ensure a flat-top condition with AND without beam for all cavities
- there is no place to adjust a lower cavity to prevent it from quenching in "no-beam" conditions with a full pulse length and maintaining the vector sum flat top
- one "solution" is to shorten the duration of the flat top in "no-beam" or "low-beam" conditions
- another solution consists of detuning the "bad" cavities and lowering their set point in such a way that these cavities will not quench when the beam is off.

More simulation work is required to predict the relationship between the flat top length and the quenching limit. Future studies also include finding the detuning and the new set point required to avoid a "bad" cavity to quench.

ANNEX: gradient and power plots comparison, with and without beam

To help understand the impact of adjusting the forward power ratio on the reflected power in different beam conditions, three cases are shown below:

1) The beam is ON, the coupling and forward power sent to individual cavities is adjusted to achieve a flat top for each cavity
2) The beam is OFF, the forward power ratio is adjusted to maintain the vector sum flat top (not for individual cavities). As a result, the lower gradient cavities will quench
3) The beam is OFF, the forward power ratio is adjusted so that the LOWEST cavity achieves a flat top. As a result, the vector sum won't be flat, BUT no cavity will quench!

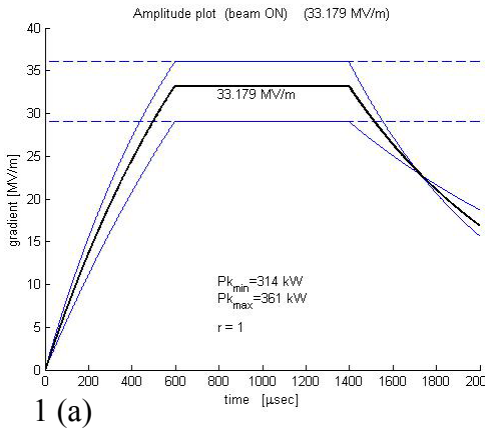
For each of the cases mentioned above, three plots are shown:

- The **gradient plot** shows the vector sum in black, the lowest and the highest cavities in blue.
- The **power plot** shows the forward power (blue), the beam power (red), the time derivative of the stored energy (green) and the reflected power (cyan) for cavity with the *lowest gradien*t
- The third plot is the same as the second but for the cavity achieving the *highest gradient*

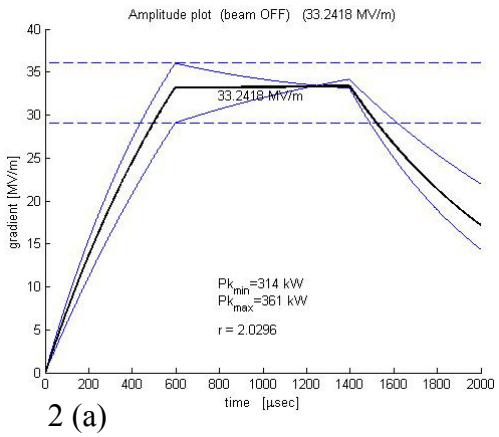
Case 1:
beam ON

Case 2:
beam OFF,
vector sum flat

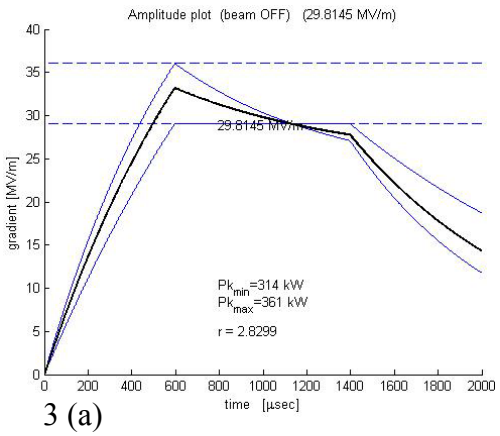
Case 3:
beam OFF
low cav. Flat



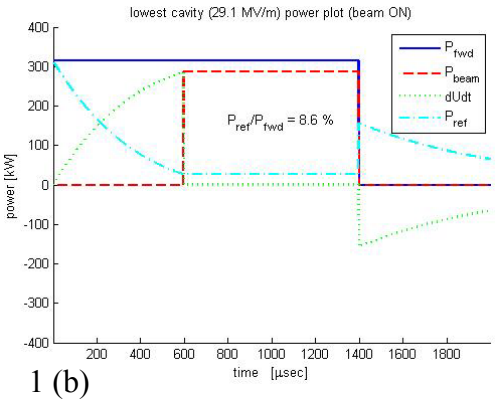
1 (a)



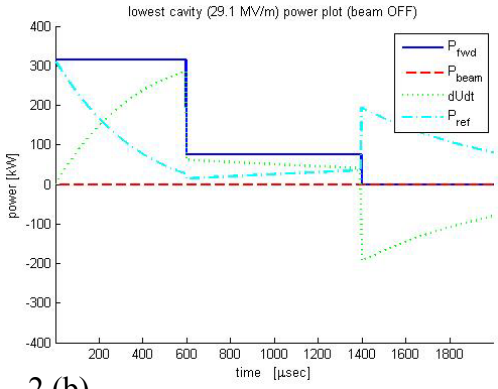
2 (a)



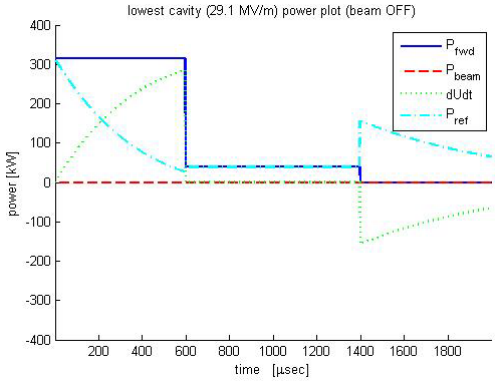
3 (a)



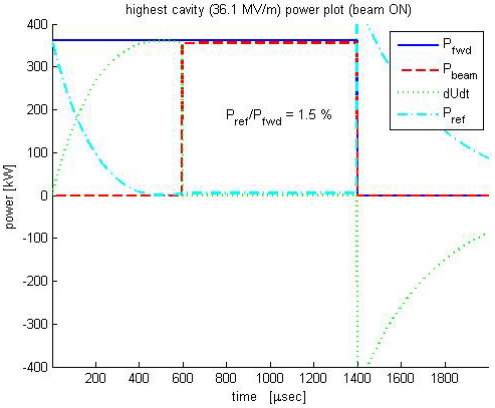
1 (b)



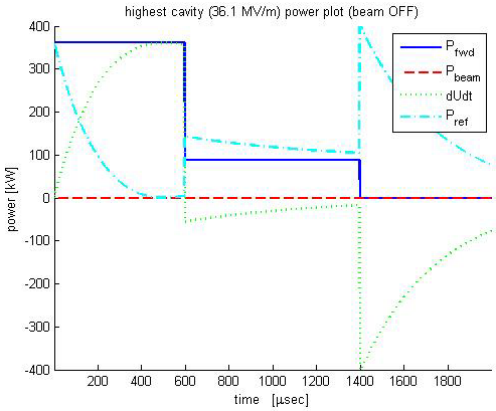
2 (b)



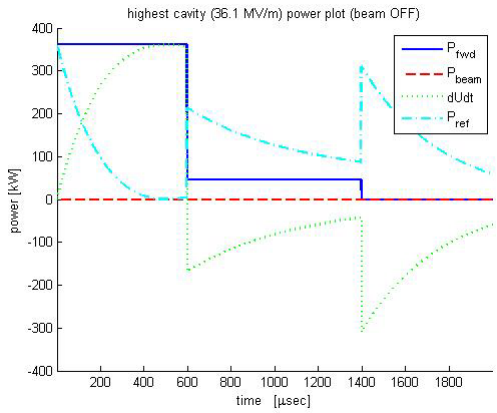
3 (b)



1 (c)



2 (c)



3 (c)

A few remarks:

- note that when the beam is on, all cavities achieve a flat top ➔ 1 (a)
- the lowest cavity hasn't reached its maximum stored energy at the injection time (hence $P_{ref} \neq 0$) ➔ 1 (b)
- the highest cavity reaches its maximum stored energy before the injection time (hence $P_{ref} \neq 0$) ➔ 1 (c)

- note that when the beam is off, maintaining a flat vector sum does NOT mean individual cavities have a flat top as well ➔ 2 (a)
- the lowest cavity's stored energy undershoots, hence $P_{ref} < P_{fwd}$ ➔ 2 (b)
- the highest cavity's stored energy overshoots, hence $P_{ref} > P_{fwd}$ ➔ 2 (c)

- note that when the ratio is adjusted to maintain the flat top for the lowest cavity, all other cavities will droop during the flat top ➔ 3 (a)
- the lowest cavity is "matched" all the forward power gets reflected when no beam is present ➔ 3(b)
- this configuration will result in more reflected power from the highest cavity ➔ compare 2 (c) and 3 (c)

- note how the **initial** forward power conditions are unchanged for all of these 3 cases (Pk_{min} = 314 kW and Pk_{max} = 361 kW) ➔ 1 (a) 2 (a) 3 (a)
- Q_L isn't changed either, only r is modified. This is important!

Another interesting case is to show how the coupling can be adjusted to zero out the reflected power of the lowest cavity. This case is shown and explained on page 7 of the document "Coupling adjustments considerations"

Conclusions:

- For a given operating gradient a cavity can achieve, there is unique combination of QL and Pk that will ensure a flat top when the beam is on.
- When the beam is off, one can adjust the ratio by which to drop the forward power to maintain a flat top either:
    - for the vector sum (then low cavities might quench)

      OR
    - for ONE and only ONE individual cavity (then the vector sum won't be flat)
- In either case, the reflected power of individual cavities won't be null