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FLATTOP OPERATION OF THE ILC ACCELERATING CRYOMODULE

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Abstract

A 500 GeV center-of-mass International Linear Collider (ILC), currently under R&D development, is foreseen as next generation High-Energy Physics (HEP) instrument [1]. Achieving 31.5 MV/m average operational accelerating gradient in a single cryomodule is a proof-of-principle for the ILC project. However the individual cavity performance may have a large spread in operating gradients, up to 20% of the nominal value[2,3]. In case of cavities performing below the average, the design parameters could be achieved by tweaking the RF distribution accordingly. We present a simple theoretical analysis of ILC cryomodule operation with a gradient spread. The difference in the gradients breaks the synchronism of a transient processes in each cavity and causes nonuniform acceleration along the bunch train. The proper solution was found to keep the accelerating module flattop operation. Finally we do the numerical efficiency estimations for the proposed RF distribution scheme based on data of actual cavities gradient spread.

INTRODUCTION

The proposed International Linear Collider requires a very low bunch energy spread along the beam train, less than 0.1% of rms value. In order to achieve this each accelerating cavity has to switch to a steady-state operation after the first bunch in a beam train coming to the cavity. The beam itself is an active load to a cavity side, thus, we can choose a matched external quality factor Q_{ext} equal to a beam quality factor Q_{beam} and proper beam arrival time to bring the cavity to a steady-state regime[4].

The situation becomes more complicated in a case of a gradient spread along the cavities in the cryomodule. If we tune Q_{ext} of each cavity to actual gradient $<G>$ then it do cause either quench or nonflatness (see Fig. 1). The reason is that each cavity has an individual filling time while a beam comes to all cavities simultaneously. The easiest way to restore a flattop operation is to force all cavities to operate at the lowest gradient. Evidently we will lose significant amount of a maximum accelerating cryomodule performance in that case. Another way is to sort the cavities in pairs of nearly equal maximum gradients [5]. This approach will help to simplify the RF distribution system but still has a disadvantage of an average cryomodule accelerating gradient loss. From the maximum achievable average gradient point of view the optimum choice is to build the variable RF distribution system with a possibility to adjust the input power and external load of each individual accelerating cavity. We will present the result of individual cavities tuning to preserve the cryomodule flattop operation and the total RF efficiency estimation as well[6].

We notice that the same problems (quench and nonflatness) arise when RF unit must operate cavities at special regimes like without RF power or at lower than a nominal beam current. The possible solutions how to correct such effects are described in [7,8].

SINGLE CAVITY OPERATION

We will analyze single accelerating cavity behavior with the following assumptions: cavity is operated at resonance (no detuning), beam is accelerated "on crest", the unloaded cavity quality factor Q_{int} is much more than the external one Q_{ext} . The cavity gradient $<G>$ is expressed by cavity voltage as $V=<G>L$, where L is a cavity length. The single cavity voltage $V(t)$ dynamic is described by the following equation:

$$V(t) = V_m(1-e^{-\frac{t}{\tau}}) - V_b(1-e^{-\frac{t-t_0}{\tau}}) , \qquad (1)$$

where V_m is the steady-state voltage in the cavity induced by a generator, V_b the voltage induced by the beam, t_0 the beam arrival time, $\tau=Q_L(2\omega_c)$ the cavity time constant, Q_L is the loaded quality factor. The flattop operation can be achieved if the time dependence vanishes after the t_0 .

$$V_b e^{-\frac{t-t_0}{\tau}} - V_m e^{-\frac{t}{\tau}} = 0 \qquad (2)$$

This gives us the proper beam arrival time:

$$t_0 = \tau \ln(\frac{V_m}{V_b}) , \qquad (3)$$

Additional requirement is the absence of a signal reflection from the cavity. One can get it by making equal external load to beam load. For this case $V_m/V_b=2$.

In reality each accelerating cavity has a different performance or a maximum induced voltage V_m before quench. Attempt to match each cavity locking to one of nominal values will cause either quench or nonflatness. The typical transient processes in the cavities are illustrated in Figure 1.

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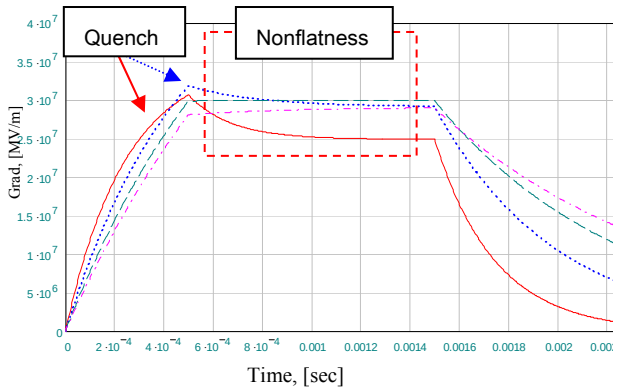


Figure 1. Gradient *vs* Time for cavities with different Q_{int} and fixed external coupling.

To eliminate the above effects and restore flattop condition we have carefully analyzed equations (1) and find the matched pairs of the input power and external quality factor separately for each cavity.

FLATTOP EQUATIONS

There is initial freedom which cavity gradient to choose as a matched gradient $<G_0>$ (index "*0*" indicates a matched parameters). At the moment of beam arrival "t_0" the voltage in each cavity should reach its nominal value V_n, proportional to a cavity accelerating gradient $<G>$. Therefore we can write:

$$V_n = V_m(1 - e^{-\frac{t_0}{\tau}}) \tag{4}$$

Taking into account the definition of cavity time constant "τ", equation (4) can be rewritten as:

$$\frac{Q_{ext}}{Q_0} = \frac{\ln(2)}{\ln[(1-\frac{V_n}{V_m})^{-1}]} \tag{5}$$

The values of V_m and V_n can be found from the following energetic relations:

$$V_m = \sqrt{Q_{\text{int}} P_m R/Q} \qquad V_n = \sqrt{Q_{beam} P_n R/Q}$$

$$P_m = \frac{4\beta_m}{(1+\beta_m)^2} P_g \qquad P_n = \frac{4\beta_n}{(1+\beta_n)^2} P_g, \tag{6}$$

where P_m and P_n are RF power coming into the cavity, P_g is input power from the generator, R/Q – normalized cavity shunt impedance, $\beta_m = Q_{int}/O_{ext}$ and $\beta_n = Q_{beam}/Q_{ext}$ are coupling coefficients. Considering that $\beta_m >> 1$ after simplification we will get:

$$\frac{Q_{ext}}{Q_0} = \frac{\ln(2)}{\ln(1+\beta_n)}, \tag{7}$$

From the relations (6) one can get:

$$(\frac{V_n}{V_0})^2 = \frac{Q_{beam} P_g \frac{4\beta_n}{(1+\beta_n)^2}}{Q_0 P_0} \tag{8}$$

According to the definition:

$$Q_{beam} = \frac{V_n}{R/Q * I}, \qquad \beta_n = \frac{Q_{beam}}{Q_{ext}} \tag{9}$$

We can express equations (9) by the parameters of a chosen matched cavity with a nominal gradient $<G_0>$.

$$Q_{beam} = \frac{<G>}{<G_0>} Q_0, \qquad \beta_n = \frac{<G>}{<G_0>} \frac{Q_0}{Q_{ext}}$$

Finally, after simplification of formulas (7) and (8) we can write:

$$\frac{Q_{ext}}{Q_0} = \frac{\ln(2)}{\ln(1+\frac{<G>}{<G_0>}\frac{Q_0}{Q_{ext}})}, \tag{8}$$

$$\frac{P_g}{P_0} = \frac{1}{4}\frac{Q_{ext}}{Q_0}(1+\frac{G}{<G_0>}\frac{Q_0}{Q_{ext}})^2 \tag{9}$$

Thus we obtaine two equations which give us the parameters of input power P_g and external coupling Q_{ext} for each cavity to perform the flattop accelerating module operation.

The typical dependencies of Q_{ext} and P_g versus cavity gradient are shown in Figs 2 and 3 respectively. One may notice that despite the initial freedom of a matched gradient choice, there is an optimum in terms of minimizing the input power reflection. Moreover, in a case of large gradient spread it is almost impossible to fulfill flattop conditions for cavities with low gradient, because of high required input power. Bellow we will give more detailed analysis in respect to the actual cavity gradients distribution.

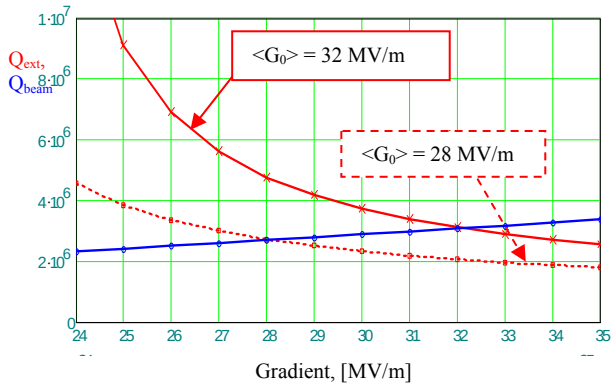


Figure 2: External coupling (red) and beam load (blue) *vs* cavity gradient

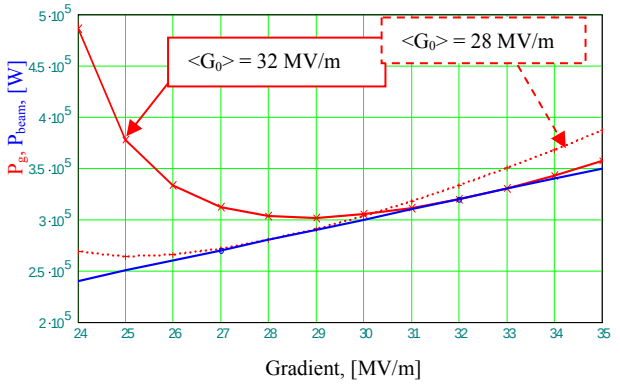


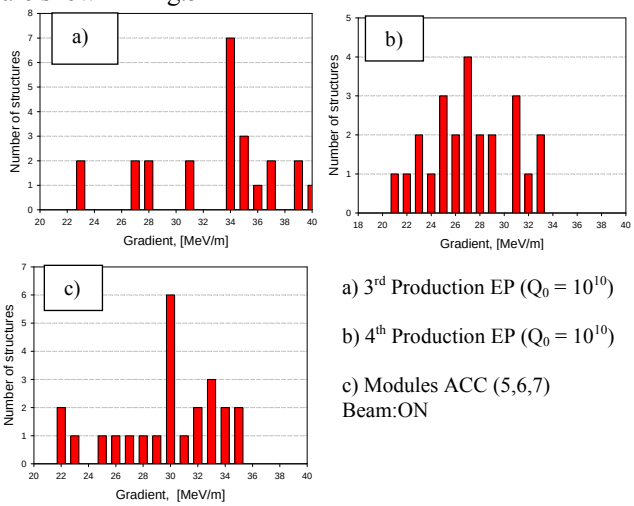
Figure 3: Input power (red) and beam power (blue) *vs* cavity gradient.

EFFICIENCY ESTIMATION

During the last decade more than a hundred superconducting accelerating structures were produced and tested at high power operation by DESY [2,3]. The statistic results of maximum achieved gradients are shown in Fig. 4. Naturally the maximum gradient is bounded to the right side by the physical limitation of a maximum magnetic field on a superconductive surface, while a lower gradient tail depends on many technological factors and has no evident limitation. Hence the plots have a visual nonsymmetrical behavior. We propose to use the Gaussian distribution $F_{gauss}(G,\sigma_g)$ with different left and right sides to describe the experimental data.

$$N(G,\sigma_g) = \left| \begin{array}{l} F_{gauss}(G,\sigma_g), G < g_m \\ F_{gauss}(G,\sigma_g/3), G > g_m \end{array} \right. , \qquad (10)$$

where g_m is a peak of a distribution. The examples of such asymmetric Gaussian distribution with its discreet variant normalized to the number of cavities in a single RF unit are shown in Fig.5



a) 3rd Production EP ($Q_0 = 10^{10}$)

b) 4th Production EP ($Q_0 = 10^{10}$)

c) Modules ACC (5,6,7) Beam:ON

Figure 4: Accelerating cavities maximum gradients distribution (based on experimental data).

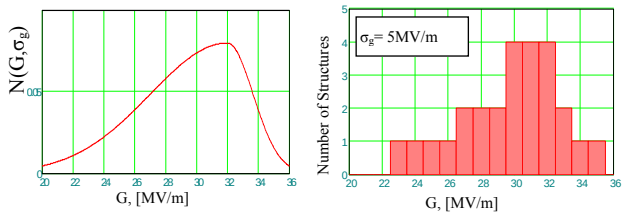


Figure 5. Asymmetrical Gaussian gradient distributions.

The drawback of obtained solution of equations (8) and (9) is that only one cavity will be perfectly matched at operating gradient. The other cavities will reflect portion of input RF power back. We can sum all these reflections and define the total power loss coefficient as:

$$\eta = \frac{\sum P_{reflected}}{P_{klystron}} \times 100\% , \qquad (11)$$

where $P_{klystron}$ is RF power coming to the whole accelerating unit from a klystron. The dependence of the total power loss versus chosen matched gradient $<G_0>$ is illustrated in Fig. 6 for two cases. The solid line is a real gradient distribution (see Fig.4 case c) and the dashed line describes the expected average loss for asymmetric distribution (10).

The minimum loss corresponding to actual gradient spread in one RF unit is about 6% while the expected average loss for many RF units is 4 %. This additional loss means that we need extra power from the klystron. Because of the limitation in a maximum klystron output power of 10 MW it is important not to overload it [1]. The total required RF power (per single RF unit) versus cavity gradient spread σ_g dependence is shown in Fig. 7.

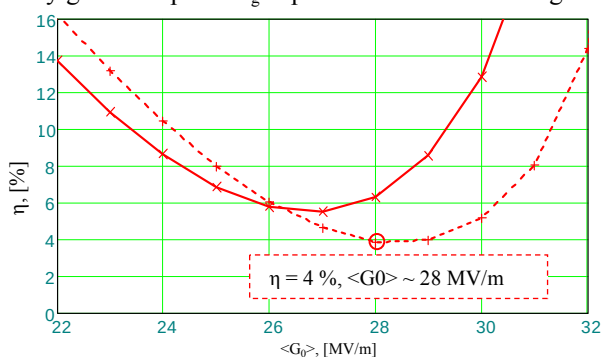


Figure 6. Total power loss *vs* matched gradient. (solid line – experimental gradients spread, dashed line – asymmetrical Gaussian distribution)

The average gradient is kept constant and equal to 31.5 MV/m. Taking into account the losses in RF distribution system (>5%) and about 10% reserved for the cavity feedback system we have to limit the maximum total required RF power below 8 MW. Therefore the maximum gradient spread σ_g in the equation (10) is limited by the value of 4 MV/m.

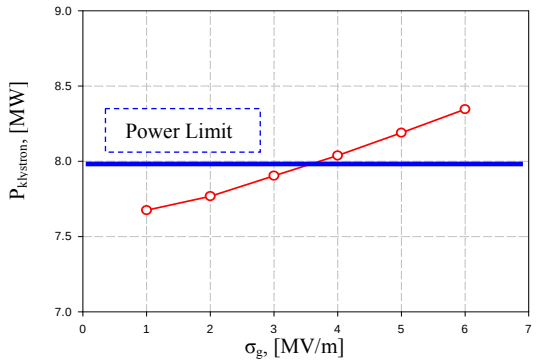


Figure 7. Total klystron RF power *vs* gradient spread. (average gradient is 31.5 MeV/m)

CONCLUSION

The flattop operation of the ILC cryomodule was analyzed under the large cavity gradient spread condition. The optimum cavity parameters were found to increase the overall efficiency. The maximum allowable accelerating gradients spread was estimated less than 4 MV/m based on the current klystron capacity limit.

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