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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

FLATTOP OPERATION OF THE ILC ACCELERATING CRYOMODULE

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A 500 GeV center-of-mass International Linear Collider (ILC), currently under R&D development, is foreseen as next-generation high-energy physics instrument [1]. Achieving of 31.5 MV/m average operational accelerating gradient in a single cryomodule is a proof-of-principle for 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 designed parameters could be achieved by tweaking the RF distribution accordingly. We present the simple theoretical analysis of ILC cryomodule operation with a gradient spread. The difference in the gradients breaks the synchronism of 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 real data of actual cavities gradient spread.

Разрабатываемый проект международного линейного коллайдера (ILC) на энергию 500 ГэВ в с. ц. м. явится новым инструментом для физики высоких энергий [1]. Для принципиального подтверждения возможности построения проекта ILC необходимо продемонстрировать работу одиночного криомодуля в режиме с однородным ускоряющим градиентом 31,5 МВ/м. Однако градиенты отдельных ускоряющих секций имеют значительный разброс, до 20 % от своего номинального значения [2, 3]. Требуемого режима работы криомодуля можно добиться понижением рабочих градиентов секций до минимального и соответствующей подстройкой системы ВЧ-распределения мощности. Мы предлагаем простой теоретический анализ возможности альтернативной работы ускорительного модуля ILC в режиме разброса градиентов отдельных секций. Различие в градиентах нарушает синхронность переходных процессов в одиночных ускоряющих резонаторах и, таким образом, приводит к неоднородному ускорению электронных сгустков во времени. В результате анализа было найдено решение, позволяющее восстановить режим работы ускоряющего модуля с однородным градиентом. В заключение мы приводим численный анализ эффективности предложенной схемы ВЧ-питания на основе экспериментальных данных о распределении ускоряющих градиентов среди уже изготовленных резонаторов.

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INTRODUCTION

The proposed International Linear Collider (ILC) 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 a first bunch in a beam train coming to

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the cavity. The beam itself is an active load to a cavity side; thus, we can choose a matched external quality factor $Q_{\rm ext}$ equal to a beam quality factor $Q_{\rm beam}$ 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 $Q_{\rm ext}$ of each cavity to actual gradient $\langle G\rangle$, then it will cause either quench or nonflatness (see Fig. 1). The reason is that each cavity has an individual filling time while a beam is coming to all cavities simultaneously. The easiest way to restore a flattop operation is to force all cavities to operate with a 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].

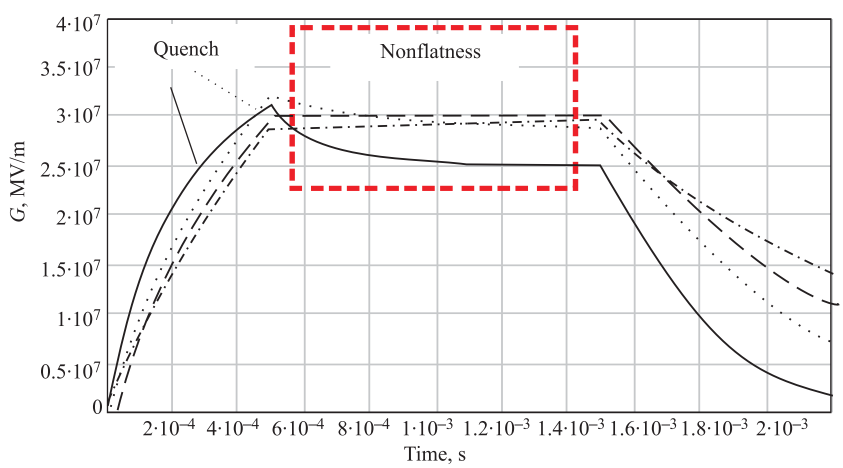

Fig. 1. Cavities gradient vs time

We have to 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 $Q_{\rm int}$ is far less than the external one $Q_{\rm ext}$. The cavity gradient $\langle G\rangle$ is expressed by cavity voltage as $V = \langle G \rangle L$, where L is a cavity length. The single cavity voltage $V(t)$ dynamic is described by the following equation:

$$V(t) = V_m \left[1 - \exp\left(-\frac{t}{\tau}\right)\right] - V_b \left[1 - \exp\left(-\frac{t - t_0}{\tau}\right)\right], \tag{1}$$

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

$$V_b \exp\left(-\frac{t - t_0}{\tau}\right) - V_m \left(-\frac{t}{\tau}\right) = 0. \tag{2}$$

It will give us the proper beam arrival time:

$$t_0 = \tau \ln\left(\frac{V_m}{V_b}\right). \tag{3}$$

Additional requirement is an absence of a signal reflection from the cavity. One can get it by making equal external load to a 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 a 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 Fig. 1.

To eliminate the above effects and restore flattop condition, we have to analyze more carefully equation (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 $\langle G_0 \rangle$ (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 $\langle G \rangle$. Therefore, we can write

$$V_n = V_m \left[1 - \exp\left(-\frac{t_0}{\tau}\right)\right]. \tag{4}$$

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

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

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

$$\begin{aligned} V_m &= \sqrt{Q_{\text{int}} P_m R/Q}, \quad V_n = \sqrt{Q_{\text{beam}} P_n R/Q}, \\ P_m &= \frac{4\beta_m}{(1+\beta_m)^2} P_g, \quad P_n = \frac{4\beta_n}{(1+\beta_n)^2} P_g, \end{aligned} \tag{6}$$

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

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

From the relations (6) one can also get

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

According to the definition

$$Q_{\rm beam} = \frac{V_n}{R/QI}, \quad \beta_n = \frac{Q_{\rm beam}}{Q_{\rm ext}}. \tag{9}$$

We can express equations (9) by the parameters of a chosen matched cavity with a nominal gradient $\langle G_0 \rangle$:

$$Q_{\rm beam} = \frac{\langle G \rangle}{\langle G_0 \rangle} Q_0, \quad \beta_n = \frac{\langle G \rangle}{\langle G_0 \rangle} \frac{Q_0}{Q_{\rm ext}}.$$

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

$$\frac{Q_{\rm ext}}{Q_0} = \frac{\ln(2)}{\ln\left(1 + \dfrac{\langle G \rangle}{\langle G_0 \rangle} \dfrac{Q_0}{Q_{\rm ext}}\right)}, \tag{10}$$

$$\frac{P_g}{P_0} = \frac{1}{4} \frac{Q_{\rm ext}}{Q_0} \left(1 + \frac{G}{\langle G_0 \rangle} \frac{Q_0}{Q_{\rm ext}}\right)^2. \tag{11}$$

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

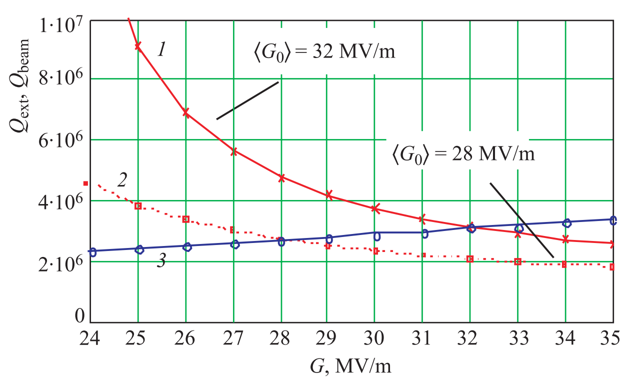

Fig. 2. External coupling (*1, 2*) and beam load (*3*) vs cavity gradient

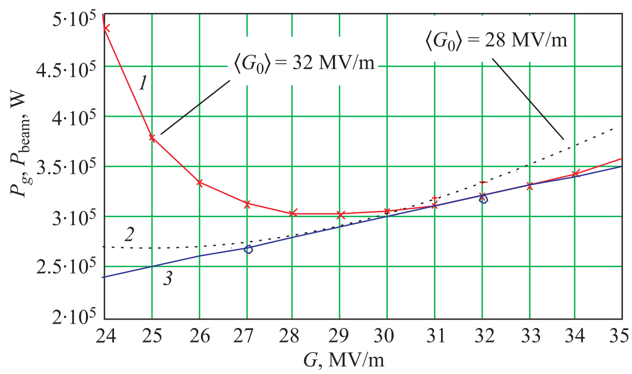

Fig. 3. Input power (*1, 2*) and beam power (*3*) vs cavity gradient

The typical dependencies of $Q_{\rm ext}$ 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, just because of too high required input power. Bellow we will give more detailed analysis in respect to the actual cavity gradients distribution.

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

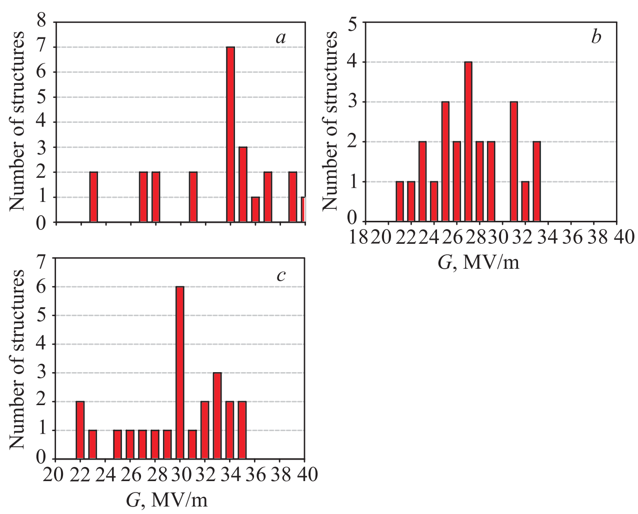

Fig. 4. Accelerating cavities maximum gradients distribution (based on experimental data). *a*) 3rd production EP ($Q_0 = 10^{10}$); *b*) 4th production EP ($Q_0 = 10^{10}$); *c*) modules ACC (5, 6, 7). Beam: ON

surface. While the distribution tail to lower gradients 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 $F_{\text{gauss}}(G, \sigma_g)$ with different left and right sides to describe the experimental data:

$$N(G, \sigma_g) = \frac{F_{\text{gauss}}(G, \sigma_g), G < g_m}{F_{\text{gauss}}(G, \sigma_g/3), G > g_m}, \tag{12}$$

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

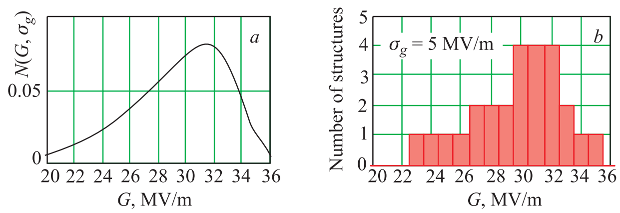

Fig. 5. Asymmetrical Gaussian gradient distributions

The drawback of the obtained solution described by Eqs. (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

$$\eta = \frac{\sum P_{\text{reflect}}}{P_{\text{klystron}}} 100\%, \tag{13}$$

where P_{klystron} is RF power coming to the whole accelerating unit from a klystron. The dependence of the total power loss on chosen matched gradient $\langle G_0 \rangle$ is illustrated in Fig. 6 for two cases. The solid line is a real gradient distribution (see Fig. 3, case *c*) and the dashed line describes the expected average loss for asymmetric distribution (12).

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

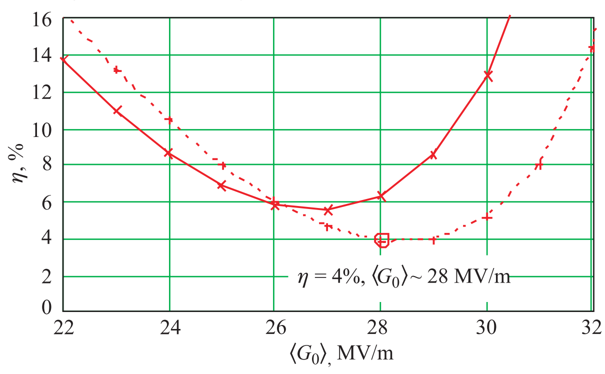

Fig. 6. Total power loss vs matched gradient (solid line — experimental gradients spread, dashed line — asymmetrical Gaussian distribution)

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.

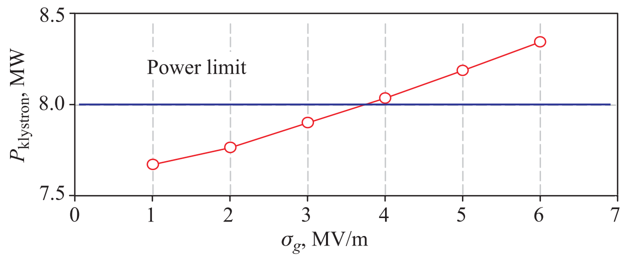

Fig. 7. Total klystron RF power vs gradient spread (average gradient is 31.5 MV/m)

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 equation (12) is limited by the value of 4 MV/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.

REFERENCES

1. International Linear Collider Reference Design Report 2007. http://media.linearcollider.org/rdr_draft_v1.pdf
2. *Padamsee H.* // TTC Meeting, FNAL, April 2007.
3. *Lange R.* // Ibid.
4. *Padamsee H.* RF Superconductivity for Accelerators. Wiley, 1998.
5. *Adolfsen C.* // GDE MAC Meeting, SLAC, April 2007.
6. *Solyak N., Khabiboulline T.* Private Commun. 2006.
7. *Branlard J. et al.* Coupling Adjustment Considerations. FNAL Intern. Note. Dec. 2006.
8. *Cancelo G.* Flattop Equations. FNAL Intern. Note. April 2007.