

GRADIENT LIMITATIONS FOR RF ACCELERATOR ON PARALLEL-COUPLED STRUCTURE

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Abstract

RF breakdown is the main gradient limitation for RF accelerator [1,2]. It is believed that all the known ways to increase the accelerating gradient have been already investigated. These are increase in the frequency of the accelerating field, reduction in the pulse duration, the optimization of cavities form, selection of operating surface materials, preparation and training of accelerating structures. In this paper, we discuss the possibility of increasing the accelerating gradient due to the circuit design, i.e., the use of the parallel-coupled accelerating structure.

INTRODUCTION

To create RF accelerators, accelerating structures of traveling and standing waves are used and improved [1]. By method of excitation, these are the structure with the serial communication where the microwave energy is supplied to one of the structure cavities and then subsequently supplied from one cavity to another. For accelerating structures with serial communication and linear electron accelerators on these structures, there are a significant number of scientific and technical problems. One of them is the breakdown problem leading to a breach of the acceleration process in the structure as a whole, its destruction.

In recent years, an interest in accelerating structures with a parallel connection has been growing. The term "parallel coupled structure" (PCS) in accelerator technology came after the publication of [3] described the structure containing the accelerating cavities fed in parallel from the lead-in coaxial waveguide. Currently, a new focus area in accelerator technology is being developing rapidly, various circuit schemes of accelerating structures are offered, features and advantages of the PCS are investigated [3-11]. We have proposed a new type accelerating PCS containing successive accelerating cavities, microwave power supplied from a common passage excitation cavity through individual communication slots [7,8]. The structure accelerating cavities are excited individually; there is almost no communication along the electromagnetic field between them. While solving the problems in creating the RF accelerators, the use of these structures can produce better results than the use of conventional structures. In this paper, the features and advantages of the PCS under solving the problem of microwave breakdown are shown by calculations and experimentally on the model.

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PCS VS STANDARD STRUCTURES

Breakdown in Standard Structure

In the structures with the serial communication under the breakdown at any point of the structure due to a "serial communication", all the microwave energy stored in the structure is absorbed, apparently, mainly near breakdown places. The accelerating field disappears, vacuum is broken due to a discharge product and this pulse is lost. To restore the necessary vacuum conditions, a period of time is required: in the standard structure with serial communication (and consistent pumping) up to 10 seconds [2]. In the accelerators containing a significant number of accelerating structures, the structure with breakdown is disconnected from the microwave power generator and pumped to restore, and the energy shortage of the accelerated beam fills by the reserve system [2].

In the standard structure - with serial communication, $\alpha_{..}$ - breakdown probability during the pulse in the whole structure is N times bigger (N - number of accelerating cavities in the structure), than the $\beta_{..}$ - breakdown probability in a certain cavity:

$$\alpha_{..} = N\beta_{..} \quad (1)$$

For example, at $N = 100$, $\alpha_{..} = 10^{-2}$ /pulse from (1), we can find $\beta_{..} = 10^{-4}$ /pulse. This means that if the loss is allowed only of every hundredth impulse, at $N = 100$, one requires the breakdown probability in the certain cavity of such a standard structure no more than $\beta_{..} = 10^{-4}$ /pulse. With the growth of the total number of cavities in the accelerator, the requirements to electrical durability of an individual cavity are increasing rapidly in accordance with the ratio (1).

Breakdown in PCS

The breakdown in the PCS occurs in a different way. We started to study the breakdown mods in the PCS in [11] on 5-cavities structure. Let us consider the results obtained in [11]. The PCS operation conditions are characterized by the pulses waveform and shown in Figure 1. Incident microwave power 1 reflected from the accelerating structure of microwave power 2 and a capacitance probe signal 3 proportional to the stored microwave power from the 5th cavity were detected (Fig.1, a - d).

The conditions without breakdown are shown in Figure 1, a. Under breakdown of the 5th cavity (Figure 1, b), all stored therein microwave energy is dissipated for 50 ns (curve 3), and is not restored till the end of the pulse.

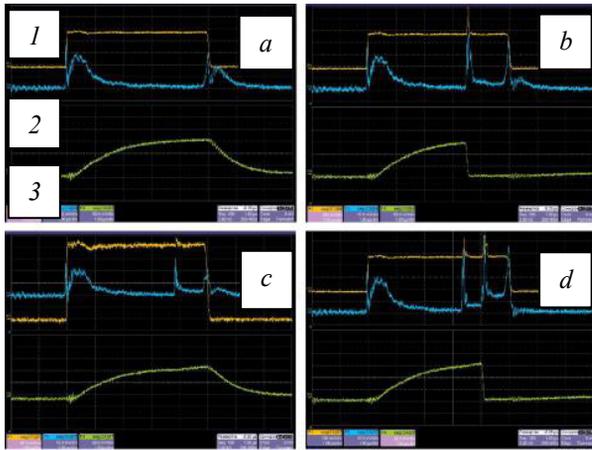


Figure 1: The oscillograms describing the PCA operation conditions [11].

During the breakdown, the cavity quality is reduced due to losses on discharge products, the frequency seems to be heavily biased, and microwave energy is no longer supplied from the supplying excitation cavity. The cavity with breakdown is disconnected from the excitation cavity. During the breakdown, a part of the stored microwave energy from the accelerating cavity is emitted to the exciting cavity and further on, to the feed waveguide (on the reflected signal 2, a short equal to 100 ns ejection is formed). The PCS now contains only 4 accelerating cavities; the coupling coefficient at the input is changed, so the reflected signal amplitude increases slightly.

If a breakdown occurs not in the fifth cavity, but in one of the first ones, then there are the processes similar to those described above, however it is hardly reflected on the fifth cavity, as shown by curve 3, Fig. 1 c. The amplitude of the pulse 3 rises slightly due to the fact that one of the structure cavities is disconnected because of the breakdown and it no longer absorbs the introduced microwave power. This power is redistributed to the remaining cavities of the structure.

Fig. 1, d shows a rare case of breakdown during one pulse in two cavities that firstly occurred in one of the first cavities and then in the fifth one. The breakdown in one of the first cavities didn't influence on the stored energy value of the fifth cavity. All the energy stored in the fifth cavity is dissipated for about 50 ns.

The experimental results show that the PCS accelerating cavities influence on each other slightly. In the PCS breakdown, only one cavity is eliminated from the acceleration mode - the one with the breakdown. Remaining cavities continue to accelerate the beam. Breakdowns occur in the cavities independently and are probabilistic in nature. Accordingly, the ratio can be obtained for the probability of breakdowns in the structure.

If $\beta_{||}$ - the probability of breakdown during the pulse in one particular cavity, so for the PCS consisting of N cavities, $\alpha_{||}$ - probability of breakdown during the same pulse in n cavities is determined by the relation:

$$\alpha_{||} = N\beta_{||}^n \quad (2)$$

If we assume that a breakdown in the PCS is acceptable, and under the breakdown in two cavities the pulse is considered as lost, from (2) with $n = 2$, $N = 100$, $\alpha_{||} = 10^{-2}$ /pulse, we can find $\beta_{||} = 10^{-2}$ /pulse. Compared with the estimates for the $\beta_{||}$ for the standard structure with serial communication, we can see that the demand on the probability of breakdown in a certain PCS cavity is significantly reduced, in this case by two orders of magnitude.

Let us estimate the requirements to accelerator cavities of considerable length, for example, to the accelerator [2], containing about 18000 standard type accelerating sections, if it is made of the PCS sections and each PCS section has 100 accelerating cavities.

For the project [2], one breakdown in one structure for 10 hours operation period is considered as acceptable at a pulse repetition frequency of 60 Hz and the total number of standard accelerating structures about 18000. This means that the maximum number (rate) of α breakdowns per one impulse is: for a standard structure $\alpha_S \approx 4.6 \times 10^{-7}$ /pulse, for one cavity (under 100 cavities in the structure, i.e., 1.8×10^6 in the accelerator cavities) $\alpha_R \approx 4.6 \times 10^{-9}$ /pulse, and for the whole accelerator in accordance with (2), $\alpha_{ACC} \approx 8.3 \times 10^{-3}$ /pulse.

Let us estimate the parameter values for the PCS. Let us assume that during one breakdown in n cavities, such a breakdown is considered as lost. Let α_n be a probability of this event. Note that α_n is equal to the maximum rate of breakdowns in the accelerator as a whole α_{ACC} . Then, assuming that $\alpha_n = 10^{-2}$ /pulse, $N = 1.8 \times 10^6$ from the ratio $\beta_{||} = (\alpha/N)^{1/n}$, we will find the values $\beta_{||}$ for different n . The data are given in the Table 1.

Table 1: $\beta_{||}$ values at various n

n	1	2	5	9
$\beta_{ }$	5.5×10^{-9}	7.4×10^{-4}	2.2×10^{-2}	0.12

The table shows that the cavity parameter values $\beta_{||}$ for the PCS are rapidly increasing if n increases as well. For example, if we assume $n = 2$, i.e., the breakdown occurs during one pulse simultaneously in two cavities of the accelerator as a whole (that is $N = 1.8 \times 10^6$ cavities), the allowable probability of breakdown in the separate cavity $\beta_{||} = 7.4 \times 10^{-4}$ /pulse. For the whole accelerator, such events will occur often.

The probability of a simultaneous breakdown in n cavities is determined by the relation (2). When $N = 1.8 \times 10^6$, $n = 2$, $\beta_{||} = 7.4 \times 10^{-4}$ /pulse, we obtain the initial value of $\alpha \approx 10^{-2}$ /pulse, i.e., every hundredth pulse will be lost. If two cavities are excluded from the acceleration mode at the same pulse, under energy set in each PCS cavity of 1 MeV, the full energy shortage will be about 2 MeV in the lost pulse. Comparing the value $\beta_{||} = 7.4 \times 10^{-4}$ /pulse for the PCS with the values $\beta_{||} = 4.6 \times 10^{-9}$ /pulse given earlier for the standard structure, we can see that the allowable probability of a breakdown in certain cavities under the same requirements to the accelerator generally differ by about 5 orders of magnitude.

So, under the breakdown probability in one cavity $\beta_{||} = 7.4 \times 10^{-4}$ /pulse, the breakdown will occur simultaneously in two cavities in the PCS accelerator in general with a probability $\alpha \approx 10^{-2}$ /pulse, i.e., every hundredth pulse will be lost. The breakdown in one of the accelerator cavities will occur practically at each pulse.

The dependence number of the breakdowns in the structure on the field strength (breakdown rate) was thoroughly investigated for the future accelerator structures. The dependence is exponential, and in accordance with the operating schedule [2], breakdown rate increases by times with increasing intensity of the accelerating field by 10% in the working area of the accelerating field strength of 50-70 MV/m. According to these data and the estimates [2] as well as to the experimental data and the estimates given in this paper, assuming a breakdown in one cavity, i.e., considering such a pulse as a working one, and in case of breakdown in two cavities, the pulse (every hundredth one) as lost one in the PCS accelerator in comparison with the standard structures, one can increase the strength of the accelerating field by 40-50%.

CONCLUSIONS

There are a significant number of problems for RF accelerators [12]. Estimating and direct experimental comparisons show the features and advantages of the PCS in comparison with conventional structures.

The RF power supply to the PCS accelerating cavities is carried out in parallel. Therefore, after each communication slot, there is power P/N , where P - power transferred to the structure, N - number of cavities. Accordingly, input elements heating is reduced by N times, field intensity in the communication slot by $N^{1/2}$.

The PCS accelerating cavities have a slight effect on each other. The breakdown is fully localized in the certain cavity. By the breakdown, the acceleration mode is not disturbed; only one cavity is disconnected from the structure. The stored energy in the structure W may be amount at several Joules (J). By the breakdown in the certain PCS cavity, energy W/N is released. For example, at $W = 10\text{J}$, $N = 100$, the ratio $W/N = 0.1\text{J}$. At such a low energy released, the consequences, i.e., heat, adsorbed gases emission, melting and evaporation of surface material, are minor. For this reason, there is no significant change in the vacuum conditions in the PCS by the breakdown. The beam is accelerated in the structure both during the current pulse and all the following.

Requirements to breakdown probability of the cavities are reduced by several times in the PCS cavities. In case of allowability of one breakdown per pulse in one of the accelerator cavities and the beam energy loss equal to 1 MeV in the accelerator in general, using the PCS can significantly raise the intensity of the accelerating gradient.

The PCS is the best accelerating structure to meet the challenges arising on the way of creation of RF accelerators.

ACKNOWLEDGEMENT

The authors thank the colleagues of ICKC, BINP SB RAS for their cooperation and assistance in the preparation of the accelerator model elements.

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