ANALYSIS OF HIGH-GRADIENT TESTS ON THE ACCELERATING STRUCTURES FOR THE KEKB INJECTOR LINAC

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Abstract

High-gradient tests were performed on three types of *S*-band, 2 m-long accelerating structures for the KEKB injector linac.

While the average accelerating field (E_{acc}) increased exponentially with the conditioning time, the field enhancement factor (β) decreased exponentially with time. The time constant of E_{acc} and β were almost the same for each structure; thus, the product of E_{acc} and β was constant during conditioning.

INTRODUCTION

The accelerating gradient of an electron/positron linac is, in the case of the KEKB injector linac, for example, 21 MV/m [1]. The linac is operated stably with an average trip rate of 0.01 times per hour for each accelerating structure. In the future, however, much higher gradient will be required: 40 MV/m for the Super KEKB factory, or 65 MV/m for an e^+-e^- linear collider. The accelerating gradient is limited by rf breakdown in the structure. So far, extensive studies have been performed on the rf breakdown of accelerating structures for many years. Dark current, momentum spectra of the dark current, radiation (γ-rays and neutrons), and pulse shape, etc. were measured and analyzed. However, our understanding of the breakdown phenomenon in the structure is far from satisfactory. In order to obtain a deeper understanding of the rf breakdown and information useful for the design, fabrication and operation of the accelerating structure, we have carried out high-gradient tests on three types of accelerating structures, as follows [2-4]:

(A) “Regular”,
(B) “w/o Crescent”,
(C) “Rinsed”.

The experimental condition, setup and results are described in references 2-4. From the tests, the following results were obtained:

(1) The maximum achieved accelerating gradient was 45 MV/m.
(2) The breakdown limit was not improved by removing a crescent-shaped cut in the couplers.
(3) By means of high-pressure, ultra-pure water rinsing, the conditioning time was shortened and the dark current was reduced.
(4) The trip rate was reduced if the gradient was decreased to below the maximum achieved gradient.

In the present work, we investigated the trend of the average accelerating field (E_{acc}) and the field enhancement factor (β), which was obtained from a Fowler-Nordheim (F. N.) plot. Consideration was given to the relation of these parameters.

MEASURED RESULTS

The rf parameters of the tested accelerating structures are given in Table 1. E_{acc} is the accelerating field and E_p is the peak surface field.

Table 1:Rf parameters of tested accelerating structures.

Frequency	2856	MHz
Phase shift per cell	2π/3	
Number of cells	54	
Iris diameter	23.75-19.70	mm
Average shunt impedance	58.3	MΩ/m
Average group velocity / *c*	0.0113	
Filling time	0.566	μs
E_p/E_{acc}	2.1	

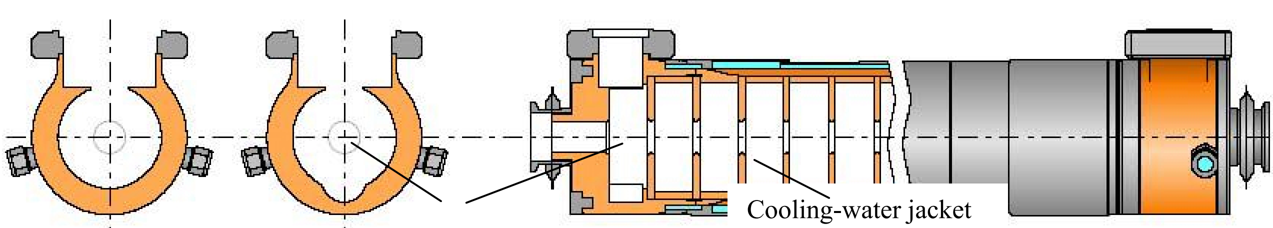

Figure 1: Cross-sectional view of the *S*-band 2 m-long accelerating structure.

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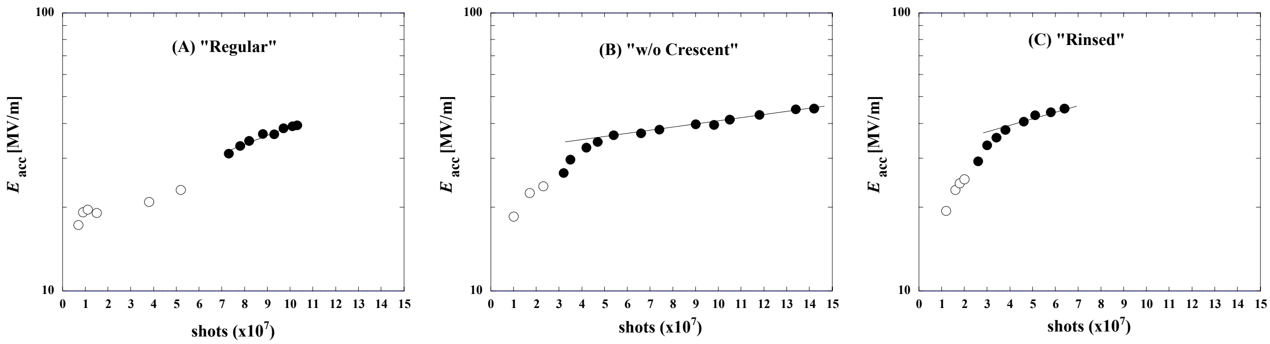

Figure 2: The relation between the accelerating field (E_{acc}) and the number of shots for the three accelerating structures. The open circle and the closed circle stand for SLED detuned and tuned, respectively.

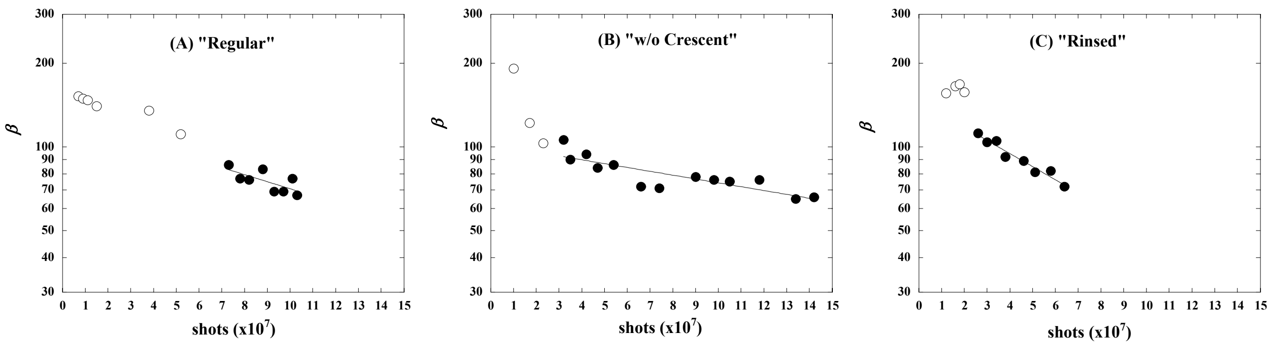

Figure 3: The relation between the field enhancement factor (β) and the number of shots for the three accelerating structures. The open circle and the closed circle stand for SLED detuned and tuned, respectively.

Fig. 2 shows the accelerating electric field gradient as a function of the number of shots for the three structures. The achieved accelerating gradient was 40 MV/m for “Regular” structure and 45 MV/m for “w/o Crescent” and “Rinsed” structures. For all of the structures, the gradient increased exponentially with time above about 35 MV/m. The gradient can be expressed as

$$E=E_0\exp(t/\tau_1). \qquad (1)$$

The time constants (τ_1) for the three structures are given in Table 2.

From the gradient of the F. N. plot, the field-enhancement factor (β) can be obtained, from which the maximum local electric field strength (E_m) can be estimated as

$$E_m=\beta E_p=2.1\beta E_{acc}. \qquad (2)$$

The relation between β and the number of shots for the three structures is shown in Fig. 3. It is shown that β decreases exponentially with time for all structures as

$$\beta=\beta_0\exp(-t/\tau_2). \qquad (3)$$

The time constants (τ_2) for the three structures are given in Table 2. It is shown that τ_1 and τ_2 have almost the same value, which is considerably different for each structure.

Table 2: Time constant of E_{acc}, β and the value of E_m.

Type	τ_1 [hours]	τ_2 [hours]	E_m [GV/m]
(A)	984	965	5.7
(B)	2140	2040	6.2
(C)	518	845	7.4

If τ_1 and τ_2 have the same value, the local electric field (E_m) should be constant independent of time. As shown in Fig. 4, the value of E_m is almost constant for the three structures during conditioning,

$$E_m = 6 \sim 7 \text{ GV/m}. \qquad (4)$$

The average values of E_m during conditioning are listed in Table 2. These values are consistent with the theoretical threshold value for metallic field emission.

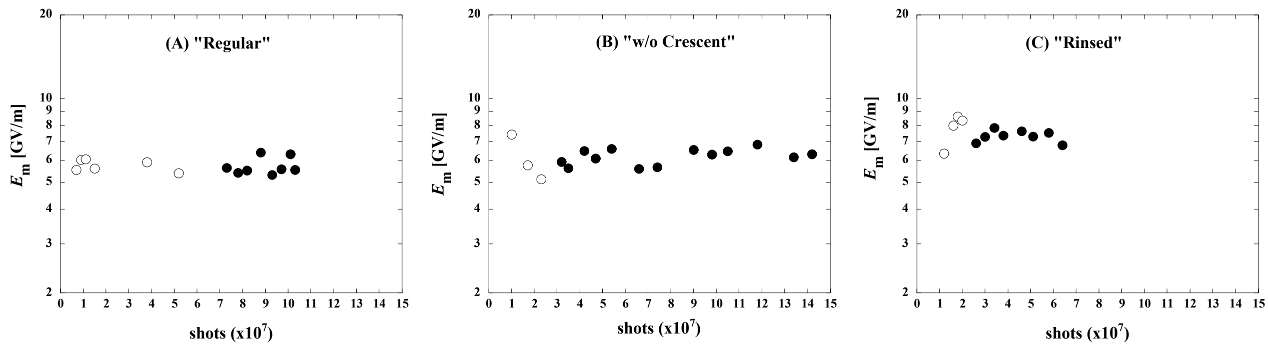

Figure 4: The relation between E_m (=βE_p) and the number of shots for the three accelerating structures. The open circle and the closed circle stand for SLED detuned and tuned, respectively.

DISCUSSION

As a reason for field enhancement, a "whisker model" is proposed in the mid-60s [5]. According to this hypothesis, if the shape of a whisker is cylinder topped with a semi- sphere (height is h and radius is r; see Fig. 5), the field- enhancement factor (β) is proportional to h/r [6]. As described in the previous section, Measured Results, E_m is constant during conditioning. Thus, from eq. (2), E_p is proportional to β^{-1}:

$$\begin{aligned} E_p &\propto \beta^{-1}, \\ &\propto (h/r)^{-1}, \end{aligned} \tag{5}$$

where r is assumed to be constant. Therefore, as conditioning progressed, the height of the whisker became lower, and thus the peak field gradient (E_p) or accelerating field (E_{acc}) became larger.

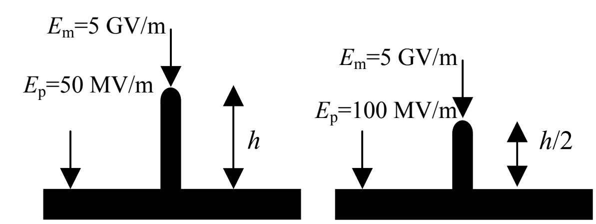

Figure 5: E_m, E_p and β for different heights of the whisker.

From the standpoint of stable operation of an accelerator, we should point out the following. As described in reference 4, it was shown by present high-gradient tests that the trip rate is reduced at the field gradient where the conditioning is finished. In the case of a type (B) structure, for example, the trip rate was 10-times per hour during conditioning. When the gradient was reduced from the maximum achieved gradient of 45 MV/m to 38 MV/m, the trip rate was reduced to 0.1 times per hour. Because the field- enhancement factor of a metal surface once conditioned becomes small, the value of E_m (βE_p) becomes small even if the accelerating field gradient (E_{acc}) is the same. The factor that determines the breakdown limit is not E_p, but E_m. Accordingly, in order to obtain a high gradient, it is necessary to reduce the field-enhancement factor. To realize this, it is necessary to do the conditioning up to a field level 20% higher than the operation point.

SUMMARY

We investigated the results of high-gradient tests of accelerating structures, and it was found that the accelerating gradient increases exponentially with time, and that the field-enhancement factor decreases exponentially with almost the same time constant. Therefore, their product is almost constant during conditioning.

We know from experience that once conditioned, the structure has a low trip rate. It might be thought that the reason for this fact is that the field-enhancement factor becomes smaller, and thus the local maximum electric field becomes lower.

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