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RFQ CONDITIONING BY GLOW DISCHARGES†

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Electrical fields are required to be as high as possible for high-current RFQs. The available field strengths, however, are limited by breakdown. The limiting fields can be increased by conditioning. Glow discharges in the critical electrode region are a useful conditioning method. Results of experiments are presented.

1 INTRODUCTION

A high current beam with a small ratio of the charge $q \times e_0$ to mass $A \times m_0$ ratio q/A of the heavy ions is needed for HIIF drivers. Accelerating these heavy ions in the low-energy part, with its high space-charge defocusing, can be done effectively with an RFQ. The RFQ output beam current is proportional to the electrode voltage and the electric (quadrupole) field strength in the RFQ. The available field strengths, however, are limited by electrical breakdowns. An attempt to increase these breakdown fields is made by the application of dc glow discharges as a conditioning method.

2 THEORETICAL BACKGROUND

The development of a spark can be understood in the following manner. Adsorbates remain inside the vacuum chamber even in spite of a careful cleaning. The electron bombardment of the electrodes during high-power operation will desorb these particles. Due to these desorbates a local volume with a higher pressure develops; the ionization rate inside is rather high.[1] Thus, the current increases sharply; the emitters on the electrodes may even melt from this local heating; and a spark occurs.

Glow discharges loosen the bound particles by ion bombardment; therefore the number of particles on the surface becomes smaller. As a result a higher current density (or, according to the simplified Fowler–Nordheim equation,[2] a higher voltage) is necessary to get desorption by electron bombardment during high-power rf operation:

$$j \sim \beta^2 E^2 \exp(-c_2/\beta E) \tag{1}$$

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Here j indicates the gap current density, c_2 is a constant which depends on the work function Φ of the electrode material, and $c_2 = 6.8\ 10^9 \times \Phi^{1.5}$ [Vm^{-1}].

Not only the desorbates, but also some electrode materials, are sputtered by glow discharges, whereby the number of emitters on the electrode surfaces may be additionally decreased.

This will change the effective field enhancement factor β, which describes the influence of the shape and the conditions of the electrode surface on the current density.[2] While originally, the β-factor only gives the geometrical field enhancement for ideal surfaces: $\beta_g = E \times g/U$, we use a $\beta = \beta_g \times \beta_m$ including the microscopic field enhancement β_m caused by whiskers, dielectric layers, etc., which normally is much bigger than the macroscopic factor: $\beta_m \gg \beta_g$. The value of β is determined experimentally by the slope of $(j/E^{2.5})$ as function of (1/E), which is called Fowler–Nordheim–Plot.[3] For the same electrode geometry (β_g = const.) the decrease of the slope indicates an improved surface condition.

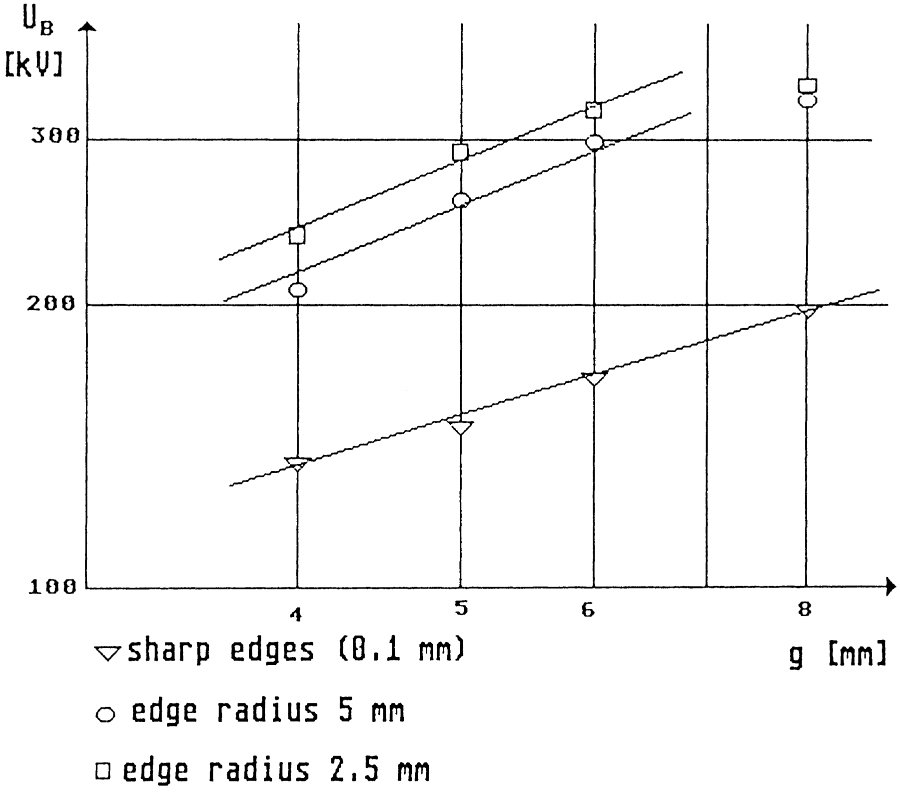

FIGURE 1 The breakdown voltage as a function of the gap width. Electrode diameter 40 mm, pulse width 1 ms, duty cycle 10%. Unexpectedly, the voltage at 5 mm edge radius is found to be somewhat lower than at 2.5 mm. This may be partly attributed to the larger electrode area at 5 mm. Nevertheless, the effect hardly exceeds the measuring error and should not be overestimated.

3 EXPERIMENTAL RESULTS

The breakdown fields and the maximum electrode voltages depend on the gap width; the rf pulse width τ_p; the repetition frequency f_p; the material and shape of the electrodes; and the preparation of the electrode surface.[4] For example, Figure 1 shows the breakdown voltage U_B as a function of the gap width g for experiments at 108.5 MHz.[5] For $g < 1$ mm the voltage U_B rises proportional to g, while the breakdown field $E_B = U_B/g$ stays constant. For larger distances (2 mm $< g <$ 8 mm) the dependence is approximately like $U_B \sim g^{0.5}$.

The breakdown voltage U_B as a function of the duty cycle $T = f_p \times \tau_p$ for different electrode geometries is given in Figure 2.[5] The breakdown voltage goes down with increasing duty cycle $U_B \sim (f_p \times \tau_p)^{-1/9}$.

There was no special surface treatment of these electrodes after machining. But it is well known that a rough electrode surface with adsorbates on it has a lower breakdown voltage. Therefore, the different methods of electrode surface preparation and conditioning will influence the breakdown voltage. Motivated by the works of, for example, Calder *et al.*,[6] Hseuh,[7] Malev & Weiser,[8] and Latham,[9] we investigated the influence of dc glow discharges at the electrode surface of rf structures on the breakdown fields.

The influence of the glow discharge on the breakdown voltage has been investigated with the rf resonator as schematically shown in Figure 3. In this "sparking" resonator

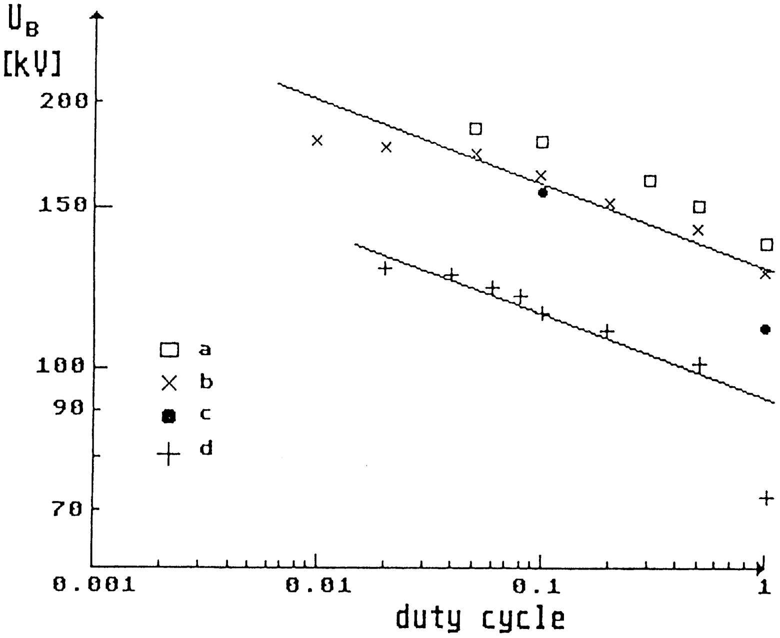

FIGURE 2 The breakdown voltage as a function of the duty cycle. (4 mm gap width; electrode diameter 28 mm.) a) "lapped." b) polished. c) plane turned. d) 4-rod RFQ module (sandblasted).

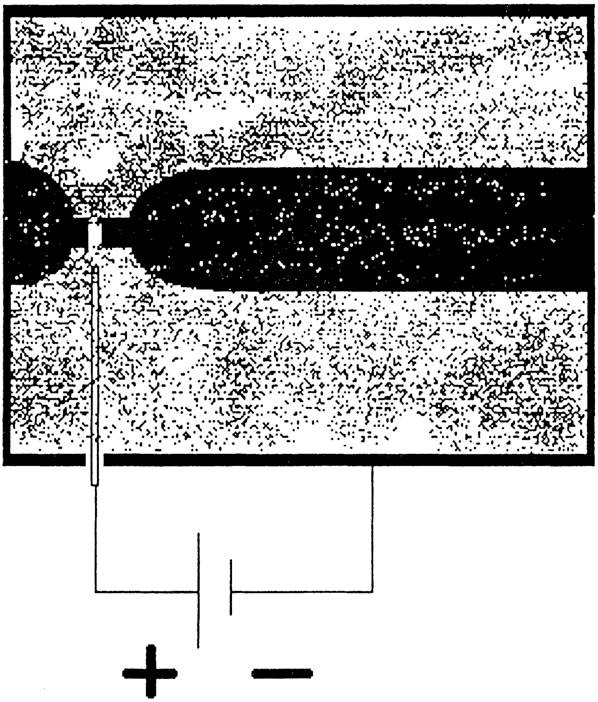

FIGURE 3 The scheme of the $\lambda/4$ coaxial resonator. For dc glow discharge conditioning the resonator acts as a cathode.

the gap width can be changed without breaking the vacuum. Compared with an RFQ the exchange processes of the electrodes are relatively simple. The high power tests are made by using a 200-kW rf amplifier, which operates at 108.5 MHz. The 4-Rod RFQ structure, as schematically shown in Figure 4, has been used for comparison. The additional anodes, shown in Figures 3 and 4, are needed for the dc glow discharge. For both the RFQ and the coaxial resonator, construction solutions have been found that allow one to move the anodes without breaking the vacuum. In the case of the RFQ resonator, the axial anode is moveable by a feedthrough.

The gap voltage and the gap current were measured by *bremsstrahlung* spectra; the breakdowns were counted automatically. The voltage, which corresponds with a spark rate of 1 spark per minute, is defined as breakdown voltage U_B.

4 DISCUSSION AND CONCLUSION

Glow discharges result in higher breakdown voltages when they are done at a pressure of about 1 Pa, e.g., with argon. The discharges can be seen as diffuse illuminations around the structures, as indicated in Figures 3 and 4.

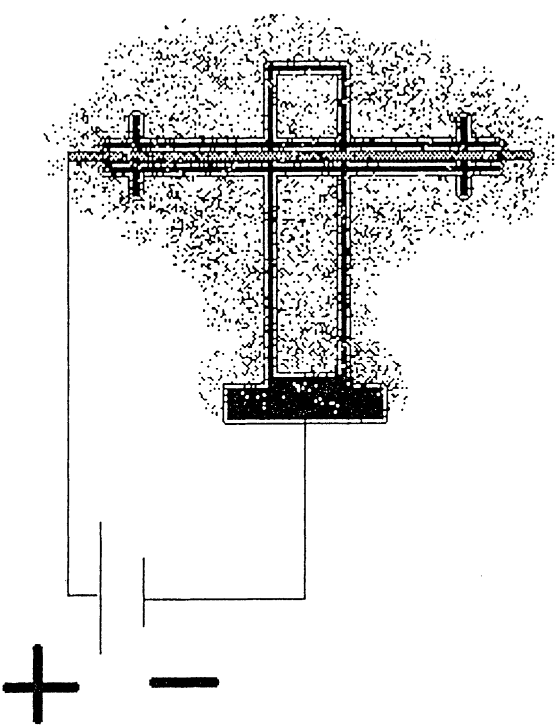

FIGURE 4 The 4-rod RFQ module. The anode between the electrodes is away during rf high power operation.

Table 1 gives a summary of the various experiments which we have done. Using the rf gap geometry, voltages up to 25% higher than those attainable with the usual conditioning techniques have been obtained. Using the RFQ module, the measured improvement was somewhat less, but still 15%. However, the conditioning effect of glow discharges is superior to "lapping," especially of large structures. Thus the glow discharges are a good way to clean and prepare rf structures *in situ*, but they cannot replace rf conditioning at high power levels as originally intended. The rf high power conditioning has to follow the dc glow discharge to reach maximum field strengths.

The effect of the dc conditioning is limited, because only ion energies up to 300 eV can be achieved in the dc glow discharge (normal cathode fall). A shielding of the critical part of the rf electrode would be necessary to raise the dc voltage, but it would change the rf properties of the resonator. By the application of glow discharges, results equivalent to a "lapped" surface are obtained. But lapping or other mechanical cleaning procedures are difficult or even impossible *in situ*. Therefore these DC discharges can be helpful for improved surface conditioning. Even the net effect of approximately 15% higher breakdown fields for the RFQ resonator can be a considerable margin because these structures work quite close to the breakdown limit; thus a small improvement may lower the spark rate drastically.

TABLE 1

Values of the β-factor and the breakdown voltage for different electrode preparations

Electrodes	β-factor	U_{Kilp} [kV]	U_B [kV]
1a	245	50	130
1b	218	50	163
1c	202	50	170
1d	162	50	200
2a	225	50	158
2e	220	50	190
3f	188	40	185
3g	222	40	160
3h	176	40	190
4i	920	77	102
4j	800	77	115

1: cylindrical Cu electrodes, diameter 28 mm, 4 mm gap width.
2: cylindrical Cu/Cr (50/50) electrodes, diameter 28 mm, 4 mm gap width.
3: cylindrical Cu electrodes, diameter 10 mm, 3 mm gap width.
4: 4-rod RFQ module.
a: abraded (abrasive paper of grain 400).
b: abraded (a.p. grain 800).
c: abraded (a.p. grain 800) and 24-h dc glow discharge.
d: abraded (a.p. grain 800) and 65-h dc glow discharge.
e: polished with polishing paste.
f: "lapped" with lapping foil; grain 9 μm–1 μm.
g: chemically etched (10 s in 45% 1.836 H_2SO_4, 45% 1.41 HNO_3 and 10% 40% HF).
h: "lapped" and 65-h dc glow discharge.
i: sandblasted.
j: sandblasted and 10-h dc glow discharge.

Future work will be done, concentrated on efforts to improve the inner electrode region of RFQs. For example, we will locally prepare those problematic areas where sparks occurred.

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