# EFFECT OF BEAM LOSSES ON RADIOL FREQUENCY QUADRUPOLE *

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*Abstract*

Most of existing high-current RFQs in the world encounter the degrade of beam transmission or unstable operation, even RF ramping can't go up to nominal design voltage after several years or long time beam commissioning. One of the main reasons is that the irradiation damage to electrode surface, caused by beam losses, influences RF performance of RFQ cavity. This is especially serious for high-current RFQ. By simulation and irradiation experiments, proton irradiation damage to copper target has been studied. The simulation results showed that normally incident proton beams with input energy lower than 1 MeV damage the copper surface in the range of one skin depth at 162.5 MHz, which indicated that almost all the lost beams with small incident angles impact RF performance of RFQ cavity. By the irradiation experiments, the damage within 60 nm depth from surface was proved to have a greater impact on surface finish. The conclusion is that low energy beam losses also need to be kept as low as possible to prolong the life of the RFQ electrodes, especially in high-current RFQ design.

## INTRODUCTION

In recent decades, some high-current RFQs have been built and operated, but how to maintain the operating life or stable operation after a long time running is still a big issue. The LEDA RFQ, which delivers a 6.7 MeV 100 mA CW proton beam at 350 MHz, is the most important high power RFQ and creates many records [1]. During the initial beam-commissioning period, the LEDA RFQ has performed well—operating for 21 hr with RFQ output currents ⩾99 mA [2]. As the running time grows, more and more lost beams struck the RFQ vane tips and the transmission dropped more frequently [3]. Ultimately, it ended by the electrodes burning after about 110 hr of running.

The J-PARC RFQ I accelerated $H^-$ to 3 MeV with 30 mA peak current and 3% duty factor, working at 324 MHz with 82.9 kV inter-electrode voltage [4]. However, because of the damage during operation and conditioning, and poor vacuum quality, sparking problems occurred and the RFQ disrupted use for a few months [5]. Then many measures were taken, such as improving the vacuum of transmission system, replacing pipeline of LEBT, updating power source and so on, but the trip rates of the RFQ cavity was still high [6]. Meanwhile, a new RFQ (RFQ II) using the same design with RFQ I but vacuum-tight cavity structure was built for spare. It is only to prove the engineering design and the fabrication technologies by high-power test. Later, based on the RFQ II, another new RFQ (RFQ III) completed the processing and replaced the previous RFQ I. Beam test in 2014 showed that because the actual transverse emittance of the ion source was larger than the design, the measured transmission of RFQ III (81%) at the nominal inter-vane voltage was lower than the design value [7].

SARAF RFQ in Israel is a 176 MHz four-rod CW RFQ, accelerating 5 mA $D^+$ to 3 MeV [8]. The first beam tests have been performed with low duty factor. However, the RFQ cavity sparks badly when the duty factor increases. Up to now neither CW operation at nominal power nor the nominal transmission can be realized [9].

From the above, we concluded several possible reasons for the degrade of beam transmission or unstable operations:

1) The design of high inter-electrode voltage causes sparking, resulting in surface damage to electrodes.
2) For high-current RFQ, strong space-charge effect and beam halo increase beam size, too small aperture causes beam collision with electrode tip surfaces easily.
3) In the pursuit of high-efficiency acceleration, RFQ length is shortened and beam transmission is sacrificed so that gentle buncher is curtailed and a lot of low-energy beams are lost at the end of it, leading to surface damage to electrode.

All these irradiation damage to electrode surface will cause more frequent sparking and larger surface resistance, thereby influencing RF performance of RFQ cavity. This paper aims at estimating the effect of irradiation damage by simulation and irradiation experiment.

## SIMULATION OF DAMAGE DEPTH

For radio-frequency accelerator, because of the skin effect, the electric current flows near the surface of the conductor and decreases exponentially with the depth from the surface. The skin depth can be calculated by

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}}$$

where ω is the angular frequency, $\sigma$ is the electric conductivity, and $\mu_0$ and $\mu_r$ are the permeability of free space and relative magnetic permeability of the conductor, respectively. When the ideal copper conductivity is $\sigma = 5.8 \times 10^7 S/m$, the skin depth of 162.5 MHz RFQ is approximately 5.2 μm,

The displacements per atom (dpa) in solid is a common representation of the irradiation effect on material properties. The formula to calculate the dpa at depth x is given by

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$$dpa(x) = \frac{F_D(x)\cdot\phi}{N}$$

where N (atoms/cm$^3$) is the atomic density of the target, $\phi$ (ions/cm$^2$) is the ion flux and $F_D(x)$ (/(cm·ion)) is the displacements (or vacancies) per ion per unit length at depth x. We can obtain the $F_D(x)$ curves for proton beams at different energies and incidence angles in copper by using SRIM—a collection of software packages that calculate interaction of ion with matter [10]. When they travel through matter, particles lost its energy on the track and the irradiation damage on the electrode is the mostly happened at its Bragg peak. Figure 1 shows the depth distributions of vacancies in copper target, corresponding to normally incident proton beams with different energies from 100 keV to 2 MeV. It can be seen that the Bragg peaks of the proton beams with energy less than 1 MeV occur in the range of one skin depth of 5.2 μm. Actually, in RFQ the incidence angles of lost particles to electrode are usually very small ( < 10°). This indicates that all the lost beams will cause damages within the skin depth, thereby affecting the RF performance of the RFQ.

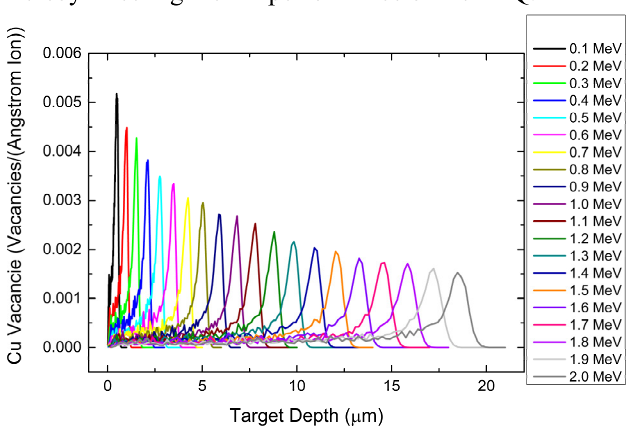


Figure 1: Depth distributions of vacancies in copper target correspond to normally incident proton beams with different energies from 100 keV to 2 MeV.

## EXPERIMENT DESIGN

Estimating the irradiation damage in RFQ, we need to confirm the energy, angle and flux of the lost beam. The detailed information of every lost ion during acceleration can be obtained by using Tracewin code [11]. Our irradiation damage study based on an optimized beam dynamics design of 100 mA proton RFQ [12]. The design parameters are shown in Table 1. It can be seen from beam losses distribution (Fig. 2) that the highest 0.02% of beams are lost in the cell 161, which is equivalent to 20 μA for 100 mA proton beams. The average energy and angle of the lost beams in this cell are 156.8 keV and 8.6°, respectively. Considering vane modulations may further increase it, the incident angle is determined to be 10°.

The ion beams for our irradiation experiment come from an ion source, which can produce proton beams up to 80 keV. As the red line shows in Fig. 3, the depth of Bragg peak is only 0.06 μm when the average 156.8 keV beams irradiate at 10° glancing incidence, similar to that caused by 10 keV normally incident proton beams. So in the irradiation experiment, we used the normally incident beams instead of the 156.8 keV beams at 10° glancing incidence.

Table 1: Design Parameters of the Proton RFQ

| Parameter | Value |
|---|---|
| Frequency [MHz] | 162.5 |
| Current [mA] | 100 |
| Input energy [keV] | 85 |
| Output energy [MeV] | 3 |
| Inter-vane Voltage [kV] | 80 |
| Kilpatrick coefficient | 1.34 |
| Aperture aperture [cm] | 0.634 |
| Vane length [m] | 8.01 |
| Cell numbers | 302 |
| Transmission [%] | 99.73 |

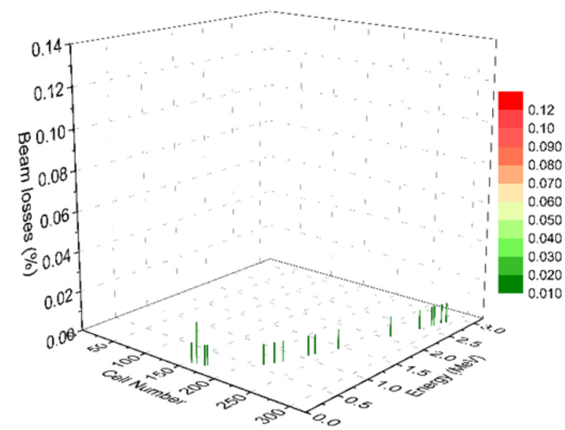


Figure 2: The beam losses and energy change with cell number in the original and optimized design.

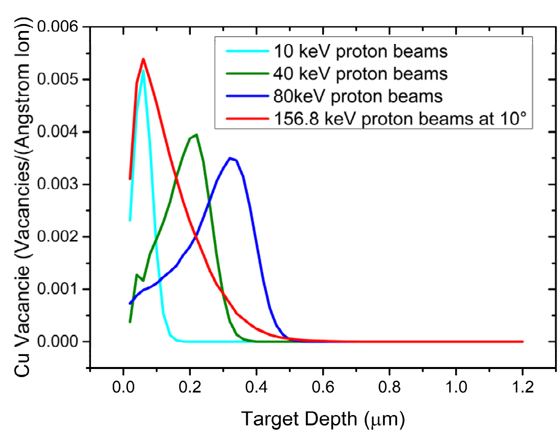


Figure 3: Depth distributions of vacancies in copper target correspond to normally incident proton beams with three different energies and the 156.8 keV proton beams at 10° glancing incidence.

## EXPERIMENTAL PROCEDURE

High purity copper samples (99.999%) with 5×5×2 mm dimensions were prepared for observing surface finish by a scanning electron microscope (SEM). Before irradiation, they were all processed using electropolishing to ensure their smooth surface. Then we studied the effect of damage depths that caused by the proton beams with different energies on the surface finish of copper. The proton flux was greatly increased for the experiment because the transmission efficiency for actual RFQ is usually lower than that of beam dynamics design and the running time is obviously much longer than irradiation time. Meanwhile, for easy comparison, the peak values of the dpa are basically equal to 5 by changing the flux. The experimental parameters are listed in Table 2.

Table 2: The Parameters of the Irradiation Experiments for the Proton Beams with Different Energies

| Parameter | E1 | E2 | E3 |
|---|---|---|---|
| Energy of proton beams [keV] | 10 | 40 | 80 |
| Flux [ions/(cm$^2$)] | $7.398\times10^{17}$ | $1.070\times10^{18}$ | $1.204\times10^{18}$ |
| The maximal dpa | 5.014 | 5.017 | 5.004 |
| Bragg peak [μm] | 0.06 | 0.22 | 0.4 |

## EXPERIMENTAL RESULT

The surface conditions of un-irradiated and irradiated copper sample are displayed in Fig. 4. After 10 keV proton beams irradiation, the surface finish of copper was greatly affected. Blocky grains and cracked hydrogen bubble can be observed obviously using SEM, even our naked eye can tell the difference between the un-irradiated and irradiated samples. While the 40 keV proton beams just lead to some surface bumps due to the 0.22 μm depth of Bragg peak (much deeper than 0.06 μm of 10 keV proton beam). Up to 80 keV, only a few grain boundary cracks and slight ups and downs are appeared. These experimental results demonstrate that the irradiation of low-energy proton beams will seriously damage the surface of copper and thus affect its RF performance.

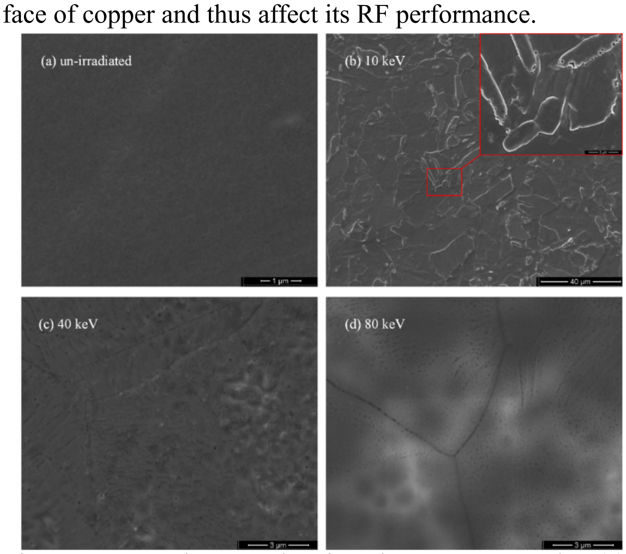


Figure 4: SEM images showing the copper samples (a) prior to irradiation and after irradiation energy of (b) 10 keV, (c) 40 keV, and (d) 80 keV.

## CONCLUSION

According to RFQ dynamics design, we simulated the surface damage of lost beams to RFQ electrodes by using SRIM. It turned out that all the lost beams in RFQ will affect the RF performance of cavity. Through the irradiation experiments, the images of SEM clearly showed that the lower energy proton beams impact the surface finish of copper more seriously. Especially for high-current RFQs, on one side, the inter-electrode voltage is usually designed relatively high to focus the beam; on the other side, the current density distributed on surface is very large due to the skin effect. The irradiation damage of low-energy lost beam to the electrode surface is bound to provoke frequent sparking in cavity and increase surface resistance, correspondingly causing unavailable high voltage and serious cavity heating, ultimately leading to unstable operation and even electrode burning. Therefore, we must pay abundant attention to low energy lost beams in high-current RFQ design. In the future, we will further study the effect of lost beams irradiation on the sheet resistance of copper.

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