ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPOPA13

PULSED DC HIGH FIELD MEASUREMENTS OF IRRADIATED AND NON-IRRADIATED ELECTRODES OF DIFFERENT MATERIALS

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Abstract

Beam loss occurs in Radio Frequency Quadrupoles (RFQ), and has been observed in the H^- linear accelerator Linac4 (L4) at CERN. To determine if beam loss can induce breakdowns, and to compare the robustness of different materials, tests have been done using pulsed high-voltage DC systems. Electrical breakdown phenomena and conditioning processes have been studied using these systems. Cathodes of different materials were irradiated with $1.2\text{x}10^{19}$ H^- p/cm^2, the estimated beam loss of the L4 RFQ over 10 days. The irradiated electrodes were installed in a system to observe if the irradiated area coincided with the breakdown locations, with pulsing parameters similar to the RFQ. Tests of irradiated and non-irradiated electrodes of the same material were done for comparison. The main difference observed was an increase in the number of breakdowns during the initial conditioning that returned to non-irradiated sample values with further running. Visual observations after irradiation show the beam centre and a halo the same diameter of the beam pipe. Breakdown clusters occur in the centre and halo regions, suggesting irradiation is not the only factor determining the breakdown probability.

BACKGROUND

The first stage of acceleration for the Large Hadron Collider (LHC) is L4 [1]. H^- ions are generated by the RF cesiated source and pass through the Low-Energy Beam Transport (LEBT) to the Radio Frequency Quadrupole (RFQ) [2]. An endoscopy of the L4 RFQ showed signs of vane surface damage and breakdowns [2]. It was postulated that the damage was due to H^- losses irradiating the Copper OFE (Cu-OFE), creating blisters causing RF breakdowns.

To gain more knowledge of the effects of irradiation on field holding, tests were carried out using a pre-existing DC setup. For this, electrodes were irradiated at the H^- source test stand, as seen in Fig. 1 [3], with the same dose as the RFQ, estimated to be $1.2\text{x}10^{19}$ H^- p/cm^2 [4].

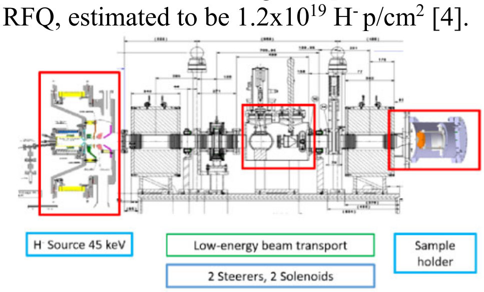

Figure 1: Irradiation setup for DC system electrodes [3].

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LARGE ELECTRODE SYSTEM

The pulsed DC Large Electrode System (LES) seen in Fig. 2, consists of 2 high precision machined electrodes placed in parallel between 20 µm and 100 µm apart in vacuum to which pulses of voltage up to 10 kV, pulse lengths between 1 µs and 1 ms, and repetition rates up to 6 kHz can be applied [5]. This system is used for the study of conditioning and vacuum breakdown phenomena. The instrumentation has the ability to detect breakdowns using voltage, current, pressure, and light and give the location of each breakdown during operation [6].

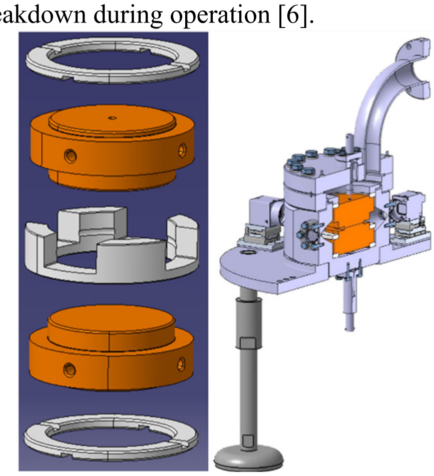

Figure 2: Exploded view of the electrode sandwich and cross section of the system.

Tests were made of different materials including Cu-OFE and CuCr1Zr, due to being the materials of the L4 and the now decommissioned L2 RFQs respectively [7]. TiAl6V4, Ta, and Nb were chosen due to their increased resistance to blistering as this was believed to be the main cause of breakdowns in the RFQ. Due to limited space, all materials except CuCr1Zr are described in this report and all results are included in the summary plots.

Two pairs of each material were tested of which one pair included an irradiated cathode. Irradiation produced visually distinct areas including the beam central area, a halo shaped by the beam pipe outlet (40 mm, 30 mm or half circle 30 mm diameter) and areas with no change, a detailed example of the areas is given in reference [8]. For these tests a small anode (40 mm or 30 mm diameter) to large cathode (60 mm or 40 mm diameter) configuration was used to avoid field enhancements on the cathode, leaving a 40 mm or 30 mm radius high-field area, depending on the electrode design used.

To replicate conditions occurring in the RFQ as closely as possible whilst keeping testing time to a minimum, a

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pulse length of 100 µs, and a repetition rate of 200 Hz were used. Once conditioned, pulse length dependence tests were also done up to the pulse length of the RFQ of 1 ms. To replicate the field of 34 MV/m of the RFQ, the LES was first conditioned to 35 MV/m before increasing the field in steps to find the limit [2]. The gap dependence effect [9], is a possible explanation for the higher fields achieved in the LES over the RFQ. The summary plot in Fig. 3 shows all the materials tested, the maximum field reached and the final stable field. With the results given in the order of the stable field achieved after irradiation.

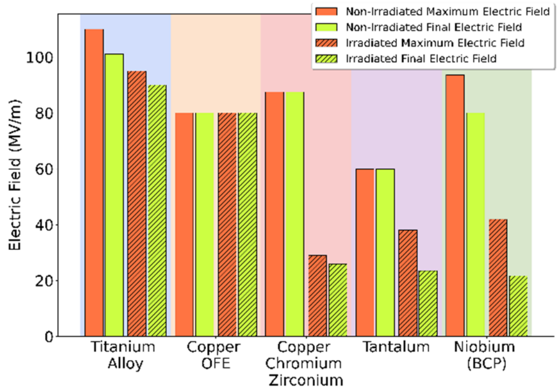

Figure 3: Summary plot of the different materials tested in order of stable field after irradiation.

RESULTS AND DISCUSION

Titanium Alloy (TiAl6V4)

After irradiation there was no evidence of modification of the surface structure due to irradiation [8]. Discoloration was seen, with a visible difference between the beam centre, halo and non-affected areas.

After conditioning it achieved the highest stable field out of all the materials, for both irradiated and non-irradiated TiAl6V4 pairs, with a small reduction in field observed for the irradiated electrodes. Both pairs of TiAl6V4 electrodes exhibited a significant decrease in operating field due to a temporal cluster of breakdowns that required reduction of the field to reduce the risk of additional clusters. As this was a feature during the conditioning of both pairs it would suggest that this is a property of TiAl6V4 rather than a spurious event. This may mean that TiAl6V4 has a tendency to accrue surface damage if conditioned too far. Overall, TiAl6V4 performed very well and was able to re-gain most of the previously achieved field without any further issues and maintain a stable field. The irradiated TiAl6V4 had a larger breakdown rate (BDR) at the start of conditioning that reduced suggesting a strong conditioning effect of the irradiated area that improved the performance.

Figure 4(b) shows the breakdown locations for the irradiated TiAl6V4 electrode. It can be seen that there was a higher concentration on one side within the halo area and not the external high field area. This suggests it is an effect of the halo combined with a possible non-parallelism between the electrodes causing a field enhancement.

Oxygen-Free Electronic Copper (Cu-OFE)

After irradiation of the cathode, blisters were observed in the beam centre area of the electrode, along with discolouration of the halo [8]. No collimator was used during irradiation, therefore for this cathode the halo is the same diameter as the anode. Therefore it was not possible to determine whether the breakdown locations were a result of the halo as there was no non-irradiated reference area of electrode to compare to.

Cu-OFE achieved the second highest stable field after irradiation, with the same stable field for the irradiated and non-irradiated pairs. Cluster in breakdowns with respect to pulses occurred multiple times during steps. To try to reduce the damage to the electrodes when clusters occurred,

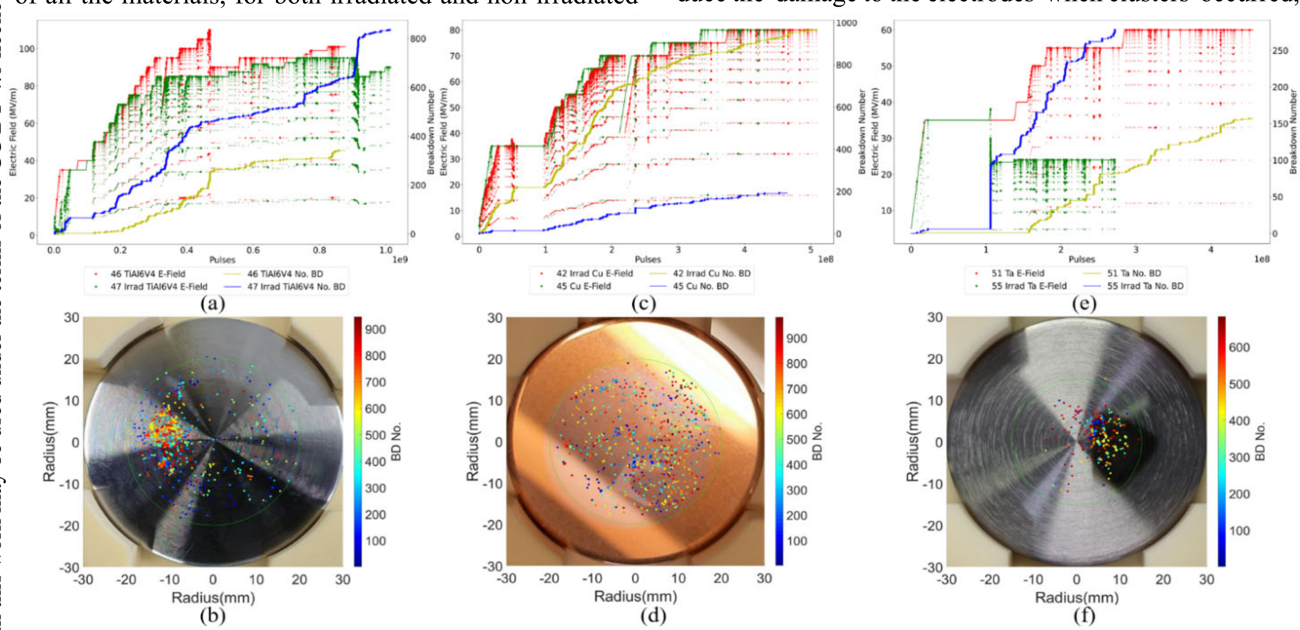

Figure 4: (a),(c), and (e) show the conditioning of the irradiated and non-irradiated pairs of electrodes and (b),(d), and (f) shows the image of the irradiated cathode overlaid with the breakdown locations coloured from dark blue to dark red as the first to last breakdown, for the different materials of TiAl6V4, Cu-OFE and Ta respectively.

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the target field was reduced to the previous stable point and pulsed before continuing to increase. It can be seen that the irradiated pair had a larger number of breakdowns at the start that decreased during conditioning to a similar level as the non-irradiated pair, suggesting that it conditioned away any breakdown inducing features caused by the irradiation.

Figure 4(d) displays the breakdown locations on the irradiated electrode where clusters occurred in different areas of the halo and not all of the beam centre area [8], suggesting that blister are not the only cause of or may not have any effect on breakdowns. It is possible that the clusters on the halo are a result of the irradiation process as the non-irradiated electrode had no cluster of this sort, with breakdowns being dispersed over the surface.

Tantalum (Ta) and Niobium (Nb)

Both Ta and Nb displayed similar results to TiAl6V4 with respect to physical defects and appearance after irradiation [8]. The beam centre area and halo for Ta can be seen in Fig. 4(f), with a half circle shape due to a change of the collimator used.

Figure 4(e) Figure 4displays the conditioning plot for the Ta electrodes, but Nb performed in a very similar way in terms of conditioning. Each irradiated pair had a large cluster of breakdowns with respect to pulses at 38 MV/m and 35 MV/m for Ta and Nb respectively. This reduced the field and the pairs were unable to recover with a stable field achieved of around 23 MV/m for each. The non-irradiated pairs did not experience any significant clusters and were able to achieve much higher fields, suggesting this is an effect of irradiation. If this is the case, both Ta and Nb would be unsuitable choices for an RFQ.

Breakdowns for the irradiated Ta were mostly clustered spatially on one side of the beam centre area. It is possible that the beam intensity could be uneven, meaning one area receives a higher dose, which may explain this effect. Unlike other materials, breakdowns were concentrated in the irradiated area of the Ta sample. Breakdowns for the Nb appeared to be spread over the halo area and not just the beam, but also may react differently to irradiation causing the significant reduction in field.

SUMMARY AND CONCLUSIONS

The best choices of material for an RFQ, based on these results are TiAl6V4 and Cu-OFE. Both TiAl6V4 pairs reached the highest stable field. However, it may display unpredictable instabilities causing a decrease in obtainable field if run close to the limit. It also has a lower conductivity so careful design and a more complex assembly process would be required if used for an RFQ. Copper gave the second best results and appears to reach the same field with an initial increase in the number of breakdowns that conditions away irradiated defects. Copper is the current material used for the L4 RFQ, and well established within the field, it would not require any changes.

It should be noted that in the case of the electrodes, the entire irradiation was done before testing. On the other hand, for the RFQ this occurs throughout running and depending on whether irradiation occurs faster or slower than the rate of conditioning could influence the stability of the structure. This is most relevant for pairs that reach similar field when comparing irradiated and non-irradiated. Re-irradiating or constant irradiation may affect the performance or the achievable field. Tests are planned for conditioning irradiated electrodes and then re-irradiating and re-conditioning to see how this impacts the performance.

Nb and Ta both had a significant reaction to the irradiation causing a large and unpredictable cluster in breakdowns that it was not possible to recover from. CuCr1Zr is not discussed in this report but can be seen in the summary plot of Fig. 3. The achievable field was greatly reduced by the irradiation and therefore it would also not be a suitable material.

Table 1: Summary of the Stable, and Maximum Field Reached and the BDR at the Stable Field for Each Material. Rows highlighted indicate that the pair was irradiated before testing.

Material	Stable Field (MV/m)	Final Field (MV/m)	Stable BDR
TiAl6V4	100	110	6.04E-7
	90	95	1.58E-7
Cu-OFE	83	83	2.05E-6
	80	80	3.13E-7
	80	80	7.5E-7
CuCr1Zr	87.5	85	5.85E-7
	26	29	1.29E-6
Ta	60	60	4.69E-7
	23	38	1.19E-6
Nb (BCP)	80	35	1.66E-6
	21.7	42	4.09E-7

Table 1 displays a summary of the materials tested, the maximum and stable field reached and the BDR at the stable field given, where highlighted rows indicate irradiation before testing. The stability at a specific field was determined based on the BDR, clusters in breakdowns with respect to pulses, occurrence of multiple breakdowns within a single pulse determined by the cameras, and proximity to a previous limit causing a large cluster. It can be seen that all materials reached relatively high fields with only irradiated pairs being restricted suggesting it is an effect of irradiation. To date Cu-OFE was tested non-irradiated twice with plans to test also irradiated whilst the other materials were only tested once. To improve reliability of these results sets of the same material should be tested.

Breakdown locations for TiAl6V4, Cu-OFE, CuCr1Zr, and Nb were distributed over the halo area and did not show preference to the beam centre area for irradiated electrodes. For the irradiated Ta electrodes, the breakdowns were mostly clustered in the beam centre area. For the non-irradiated electrodes breakdowns were distributed over the whole high field area. Analysis of the areas of the irradiated electrodes suggests a possible higher carbon content in the beam and halo areas with also possible electrons, H neutrals and stray H^-.

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