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BEAM DYNAMICS AND RF DESIGN STUDIES FOR A PROPOSED NEW RFQ FOR CERN LINAC4

H. W. Pommerenke[*], G. Bellodi, A. Grudiev, S. Kumar, A. Lombardi, CERN, Geneva, Switzerland

Abstract

The 352 MHz Linac4-RFQ is the first rf accelerating structure of the CERN accelerator complex, accelerating an H- beam to 3 MeV. After successful commissioning in 2013, superficial vane damage has been observed in 2020. In view that the RFQ is a single point of failure, in parallel to the production of a near identical spare (RFQ2), design studies on a longer-term upgrade have been launched: Linac4-RFQ3. Main goals are to achieve a design with higher beam acceptance, reduced beam losses, and reduced rf breakdown rate. Several versions of RFQ are under study: conventional RFQs built by brazing copper, as well as an RFQ with titanium vane tips (brazed on copper). High-gradient experiments suggest that titanium vane tips support higher surface fields compared to copper, up to 40 MV/m, and are more resistant against beam irradiation. In this paper, we present beam dynamics and rf design of various RFQ3 designs.

INTRODUCTION

Linac4-RFQ1, currently installed in the tunnel, was designed when the source development was not yet completed and an emittance of 0.25 π mm mrad (rms normalized) was used as input design parameter. A safety factor was built into the design fixing the RFQ acceptance to about 0.35 π mm mrad for a current of 70 mA. Whereas such value was eventually achieved for source beam peak currents up to 40 mA, any larger current was extracted with an emittance that exceeded the RFQ acceptance: For a peak current of 70 mA an emittance of 0.5 π mm mrad, has been measured at the Linac4 source test stand (Fig. 1).

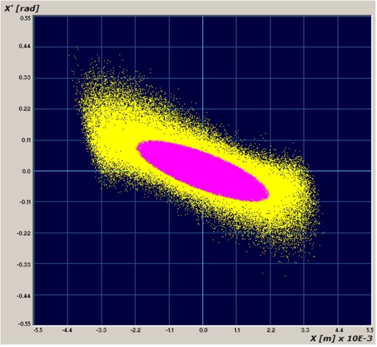

Figure 1: Measured beam out of Linac4 source (yellow) vs. RFQ1 acceptance (pink). The expected transmission (TOUTATIS [1]) is only 75 %.

To overcome this bottleneck, a study was launched to design an RFQ better targeted to the source performance and yet maintaining several of the successful design choices of the original RFQ: full compatibility with Linac4 in terms of input and output energy and final longitudinal emittance, a two-term potential vane profile, a constant average aperture radius and a constant transverse radius of curvature for easier tuning (constant capacitance) and the possibility of machining with a 2D cutter.

DESIGN GUIDELINES

The main redesign effort has been to balance the phase ramp with the increased input transverse emittance and optimize the trade-off between the transverse acceptance and the final longitudinal emittance. The result of this optimization has been either a longer RFQ or a higher surface electric field on the vane tips. The main RFQ parameters for three different solutions are reported in Table 1. All solutions present a transmission higher than 90 % for a beam current of 70 mA in an emittance of 0.5 π mm mrad. Figure 2 compares the beam transmissions of RFQ1 with the proposed designs as function of input beam emittance. It is noted that the acceptance for a 60 mA beam from the source is doubled with respect to RFQ1: A current of 60 mA needs to fit in an emittance of 0.4 π mm mrad for RFQ1, but in just 0.8 π mm mrad for RFQ3 to give 48 mA out of the RFQ.

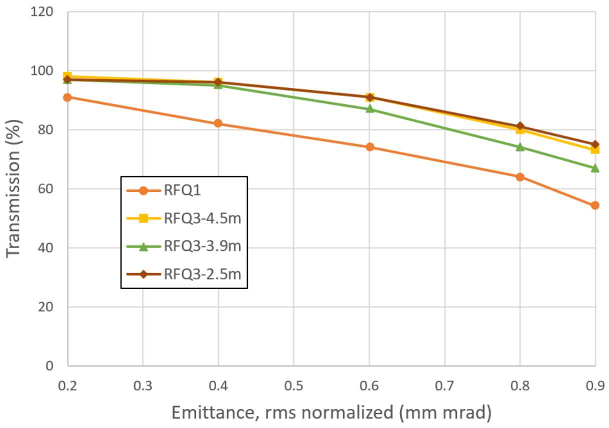

Figure 2: Performance comparison: Transmission vs. emittance for fixed beam current of 60 mA for RFQ1 and considered RFQ3 designs.

Like most RFQs, Linac4-RFQ1 has been designed with the Kilpatrick criterion [2] as ultimate surface electric field limit. In 1961, Maitland [3] pointed out the "gap scaling" relation

$$E_{\mathrm{norm}} = \frac{V}{V_{\mathrm{DC}}} \left(\frac{d_{\mathrm{DC}}}{d} \right)^{\alpha} , \tag{1}$$

for dc electrodes separated by distance d subject to pulsed dc voltage V. This has been recently confirmed through dc sparking tests at CERN, where empirically $V_{\mathrm{DC}} = 7.75\,\mathrm{kV}$,

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[*] hermann.winrich.pommerenke@cern.ch

Table 1: Key Parameters of Linac4-RFQ1 and Several RFQ3 Designs.

	RFQ1	**RFQ3-3.9**	**RFQ3-4.5**	**RFQ3-2.5**	
Length	3.1	3.9	4.5	2.5	m
Material	Cu OFE	Cu OFE	Cu OFE	Ti vanes	
Dipole rods required	yes	yes	no	yes	
Vane voltage	78	79	79	120	kV
Max. surf. E-field	34	33	33	44	MV/m
Peak rf losses	390	650	750	960	kW
Average aperture r_0	3.3	3.2	3.2	4.1	mm
Transverse radius ρ/r_0	0.85	0.69	0.84	1.00	
Maximum modulation m	2.4	1.8	1.5	2.2	
Minimum aperture	1.8	2.2	2.5	2.4	mm
Focusing strength B	5.5	5.8	5.9	5.5	
Phase at gentle buncher	-32	-32	-35	-32	deg
Transmission (70 mA, 0.5 π mm mrad)	80	95	93	91	%

$d_{\mathrm{DC}} = 100\,\mu\mathrm{m}$, $\alpha = 0.7$. For an acceptable breakdown rate with Copper OFE, E_{norm} should not exceed ≈ 1.05 [4]. In an RFQ, an effective gap can be defined in terms of vane voltage and surface electric field, $d = V_0/E_s$, which turns out to be close to the average aperture r_0. Electric field levels and breakdown rates reached in the dc experiments, in Linac4-RFQ1 (34 MV/m, 79 kV) and in other RFQs are consistent under this law. However, other established high-gradient limits are less applicable [5, pp. 35ff.]. Therefore, the gap scaling criteria is used as the main electric surface field limit for the following RFQ designs (Fig. 3).

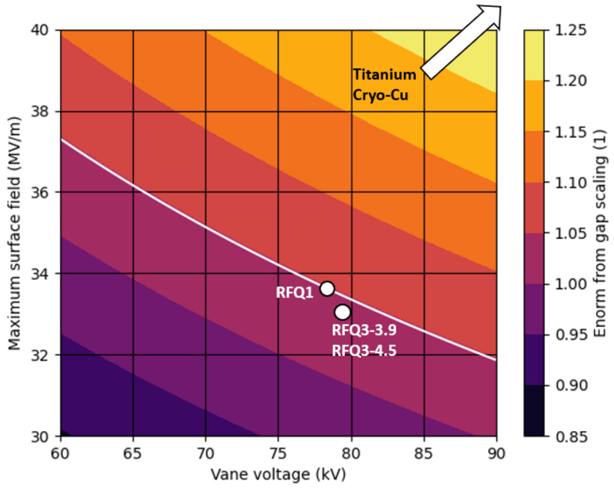

Figure 3: Graphical representation of gap scaling (1) of surface electric field with RFQ1 and RFQ3 designs.

OFE COPPER RFQ

RFQ3-3.9 represents a conservative design fulfilling the above-mentioned criteria. It is 25 % longer than RFQ1 while maintaining practically the same voltage and surface fields. To gain confidence in the design tool (PARI/PARMTEQ [6]), we cross-checked the surface electric field predicted with 3D FEM simulations (COMSOL Multiphysics® [7]) and observed excellent agreement (Fig. 4). RFQ3-3.9 would feature a conventional rf design with dipole stabilization rods to control spectral margins aroung the operating mode.

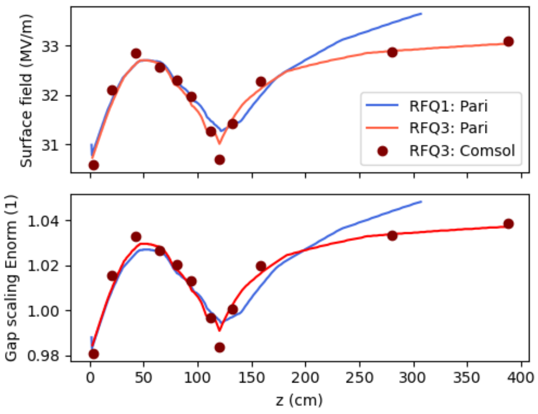

Figure 4: Surface electric field in absolute (top) and gap scaling representation (bottom) as predicted by PARMTEQ vs. COMSOL simulation results, for copper RFQ3-3.9.

In addition, a 4.5 m-long design has been considered. The length was chosen such that the dipole modes of this RFQ would be placed with maximum spectral margins around the operating mode. This technique has been proposed in Refs. [8, 9]. It avoids using dipole stabilization rods on the end plates, reducing manufacturing complexity. While the rf surface losses on the rods are removed, the overall losses are still 15 % higher than in RFQ3-3.9 because they are dominated by the overall RFQ length.

HIGH-FIELD RFQ

High-gradient experiments suggest that alternative materials support higher surface electric fields than room-temperature copper. An RFQ with grade 5 titanium (Ti-6Al-4V) vane tips brazed or bonded on copper, could support fields up to 40 MV/m [10] according to the gap scaling.

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Cryogenic copper might allow even 50 MV/m [11, 12]. To get a feeling of what beam dynamics designs are possible with these surface fields, a limit of 45 MV/m at 120 kV vane voltage was chosen. Parameters of this possible high-field RFQ, labeled RFQ3-2.5, are listed in Table 1. The high field allows for retaining the same focusing strength as the previous design, but with much larger r_0 and shorter length. However, rf power losses increase significantly because of the high voltage. PARMTEQ particle tracking results are presented in Fig. 5.

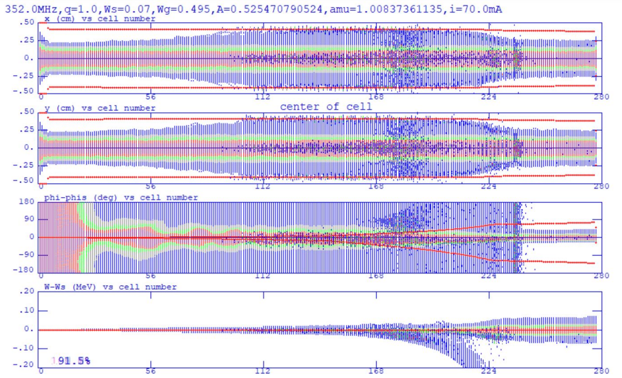

Figure 5: PARMTEQ particle tracking results of high-field design RFQ3-2.5.

To reduce breakdown probability, the titanium tip of the vane must extend far enough from the beam axis to ensure that the field at the joint is sufficiently low. However, both electrical and thermal conductivity of titanium are poor compared to copper. Both rf losses and temperature rise during operation increase with the titanium thickness, as can be seen in Fig. 6. 2D multiphysics simulation results for a joint at 8 mm from the beam axis are shown in Fig. 7; the temperature rise is tripled compared to an RFQ made entirely from copper. This effect is even more severe at the downstream end of the RFQ since the cooling channels cannot extend into the vane nose and the vanes themselves are locally thicker because of the modulation. Figure 8 shows that the 3D temperature rise is up to 20 times higher than the 2D result. The temperature gradient will lead to strong deformation and stresses during operation and brazing.

CONCLUSION

Design studies on a long-term upgrade of CERN Linac4-RFQ have been presented: Linac4-RFQ3. Taking into account beam parameters recently measured at the Linac4 source, the new designs feature higher beam acceptance, reduced beam losses, and reduced rf breakdown rate. Several versions have been considered: conventional RFQs built by brazing copper and an RFQ with titanium vane tips. Conventional designs could be readily manufactured with 2D cutters and well-known brazing techniques. More R & D would be required for the titanium vane RFQ, both for manufacturing the bimetallic structure and for validating high-gradient performance.

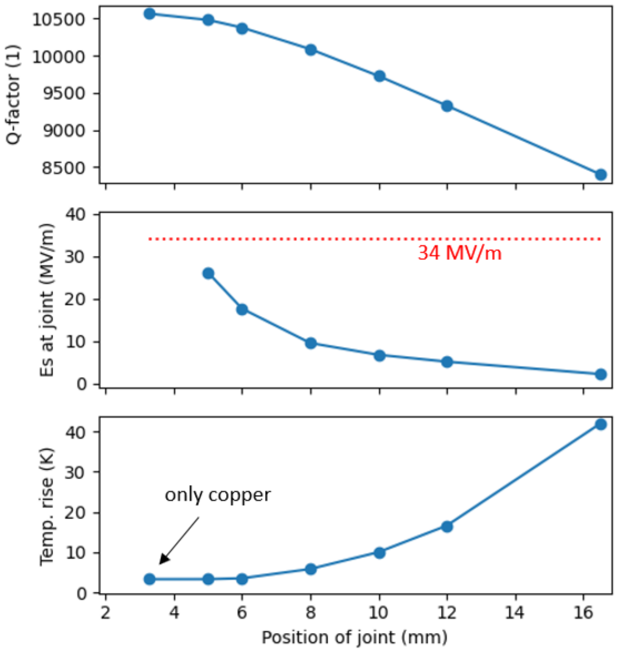

Figure 6: Reduction of Q, surface field at joint, and 2D temperature rise as function of Ti-Cu joint position from beam axis. Values for RFQ1 geometry with V_0 = 79 kV and 5 % duty factor is shown.

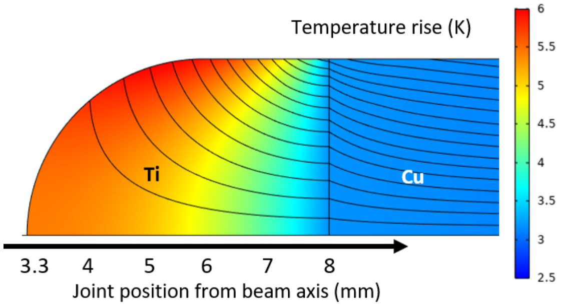

Figure 7: 2D temperature rise field in the vane tip made from titanium.

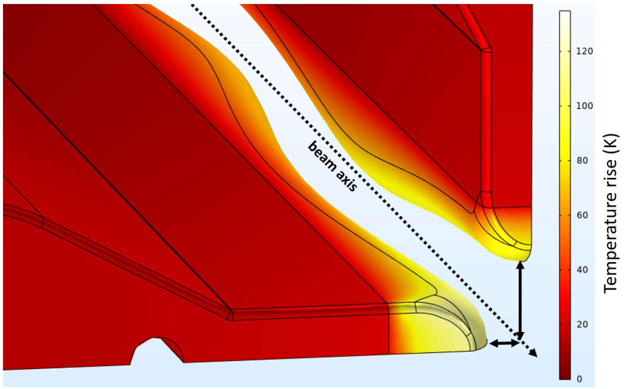

Figure 8: 3D temperature rise field in the titanium vane tip at the RFQ downstream end.

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