BEAM DYNAMICS FOR A HIGH CURRENT 3 MeV, 325 MHz LADDER-RFQ*

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Abstract

After the successful measurements with a 0.8 m prototype (see Fig. 1), a 3.3 m Ladder-RFQ is under construction at IAP, Goethe University Frankfurt. It is designed to accelerate protons from 95 keV to 3 MeV according to the design parameters of the Proton Linac at FAIR. The development of an adequate beam dynamics design was done in close collaboration with the IAP resonator design team. A constant vane curvature radius and at the same time a flat voltage distribution along the RFQ was reached by implantation of the modulated vane geometry into CST Microwave Studio RF field simulations. Points of reference for the beam dynamics layout are the beam dynamics designs of C. Zhang [1] and A. Lombardi [2]. The Code RFQGen [3] was used for the beam dynamics simulations. In order to increase the transmission and to reduce the longitudinal and transversal exit emittances[1], the evolution of the modulation parameter m within the first 90 cells was investigated in detail. This paper presents the simulation results of this study.

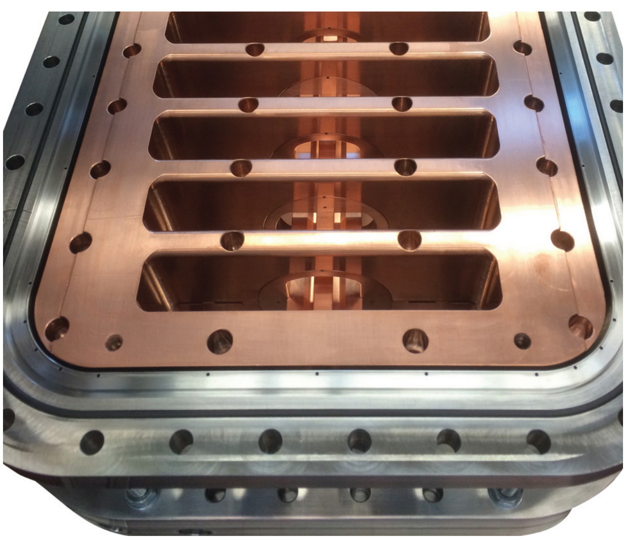

Figure 1: Photo of the Ladder-RFQ prototype (courtesy of M. Schütt). The upper steel-tank was removed to get a view of the inner ring-ladder structure.

ELECTRIC FIELD DISTRIBUTION

An estimation for the maximum applicable electric field E_k is done with the Kilpatrick criterion [4]:

$$f = 1.643\, E_k^2 \, \exp(-8.5/E_k).$$

For resonator frequency f = 325.224 MHz, E_k results to 17.85 MV/m. RFQGen calculates the maximum actually applied surface field E_S to 43.12 MV/m, which is in agreement with the value simulated by CST Microwave Studio. The Kilpatrick factor (bravery factor) b = E_S/E_k amounts to approx. 2.58. Figure 2 shows the absolute electric field distribution at the center (left) and exit (right) of an RFQ cell. At the center, a nearly ideal quadrupole symmetry is realized. Thus, the field distribution at the center is similar to that of an ideal electric quadrupole channel, where the absolute electric field vanishes at the beam axis and rises linearly with the value of polar coordinate r.

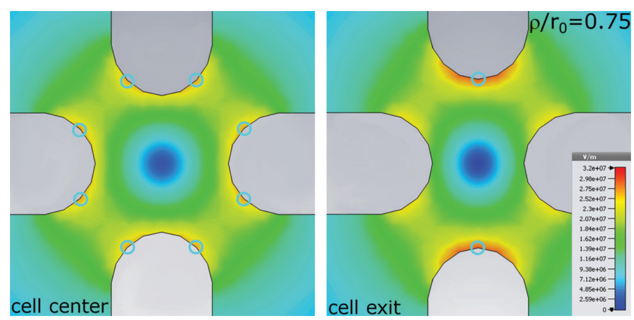

Figure 2: CST MWS contour plots (linear scaling) of the absolute electric field in the x-y-plane (the beam axis is oriented in the z-direction) at the center (left) and exit (right) of cell 179 (courtesy of M. Schütt). The ratio of the transverse radius of curvature of vane tip ρ and the mid-cell radius r_0 is 0.75. At the cell center, where the horizontal and vertical apertures are equal to r_0 = 2.96 mm and a nearly ideal quadrupole symmetry is realized, the highest value of approx. 26 MV/m occurs for the nearest neighbor distance d_{min} = 2.88 mm. At the cell exit, the maximum value of approx. 29 MV/m occurs at the vertical electrode tips. The positions of the field maxima are indicated by cyan circles. Please note that these contour plots are associated with a stored energy of 1 J, which corresponds to an electrode voltage of approx. 60 kV. For an electrode voltage of 96 kV, the maximum electric fields are approx. 42 MV/m (cell center) and 46 MV/m (cell exit), respectively.

BEAM DYNAMICS DESIGN

The Code RFQGen by L. Young was used for the beam dynamics calculations. In consideration of the source beam as given by N. Chauvin [5] (see Table 1) and the design parameters of the Proton Linac at FAIR, the design was

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1 For this paper, the emittance values refer to the normalized rms emittances.

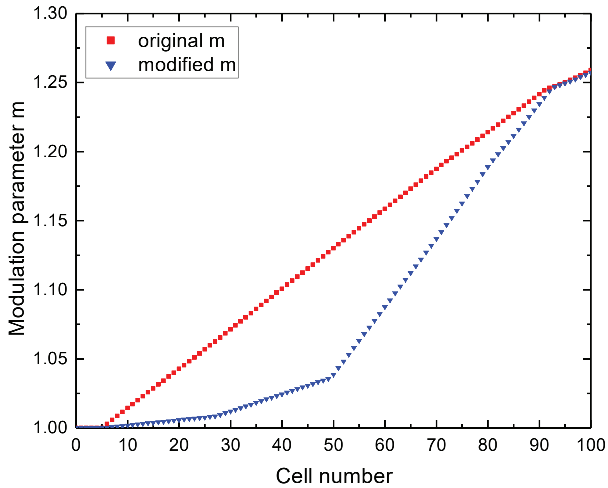

Figure 3: Plots of the modulation parameter m against the cell number for two cases: the red graph shows the original m-shape as produced by RFQGen, whereas the blue graph shows the modified m-shape.

tested for the most promising number of radial matching cells, which turned out to be 4. In this case, the exit particle distribution as shown in the second column ('original m') of Table 2 was obtained. The longitudinal exit emittance was 0.44 MeV deg (required: 0.35 MeV deg), and the exit x- and y-emittances were 0.36 π mm mrad and 0.32 π mm mrad, respectively (required: 0.30 π mm mrad).

Table 1: Input Beam Parameters (top) and RFQGen Settings (bottom) for Beam Dynamics Simulations

Parameter	Value
Entrance Energy	95 keV
Beam Current	70 mA
Transversal $\varepsilon_{n,rms}$	$0.2\,\pi\,mm\,mrad$
Twiss Parameter $\alpha_{x/y,in}$	0.44
Twiss Parameter $\beta_{x/y,in}$	4 cm/rad
Frequency	325.224 MHz
Electrode Voltage	96 kV
ρ/r_0	0.75
Number of RM Cells	4
Desired Exit Energy	3 MeV
Entrance Particle Distribution	4D Waterbag
Number of Macro Particles	10^5
Exit Synchronous Phase ϕ_{out}	90°

VARIATION OF THE MODULATION PARAMETER SHAPE

In the following step, modification of the shape of modulation parameter m from the one generated by RFQGen for the first 90 cells (see Fig. 3) led to improved traversal and longitudinal exit emittances (cf. Table 2 and Figs. 4 and 5). The improved longitudinal exit emittance was 0.28 MeV deg (required: 0.35 MeV deg), and the exit x- and y-emittances were 0.31 π mm mrad and 0.33 π mm mrad, respectively (required: 0.30 π mm mrad). The signs of the α-twiss parameters in Table 2 contain the information that in case of the original m-shape, the exit beam is convergent in the x-plane and divergent in the y-plane and vice versa in case of the modified m-shape. Transmission could be increased from 93.02 % to 96.79 %, and the number of cells rose from 332 to 335.

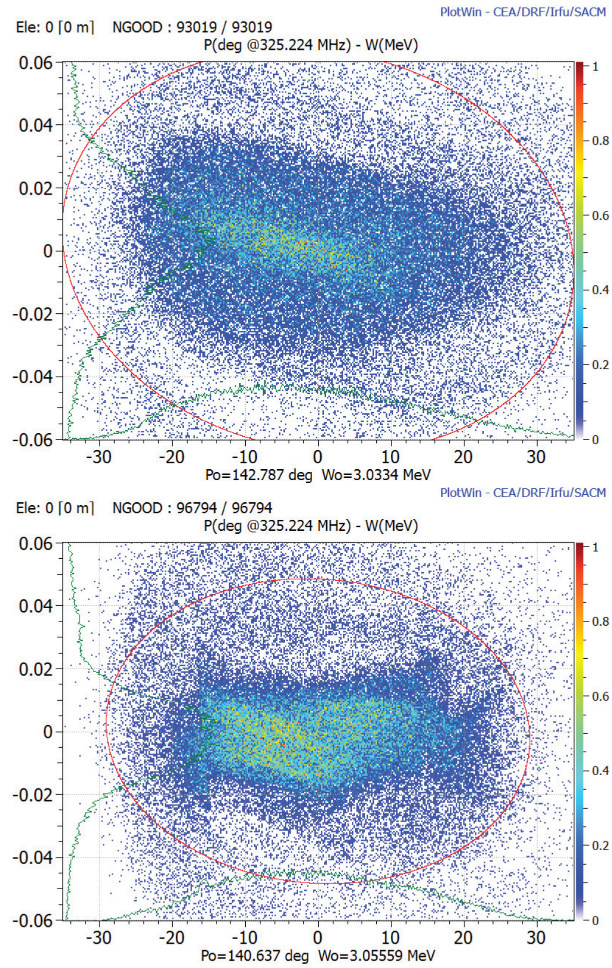

Figure 4: Plots of the longitudinal phase space distribution projections (green curves) at the RFQ exit in case of the original (top) and the modified (bottom) m-shape. The colors of the scatter plots refer to the normalized (macro) particle density (cf. scales at the right frames of the plots). The red ellipses refer to the normalized 90 % emittances.

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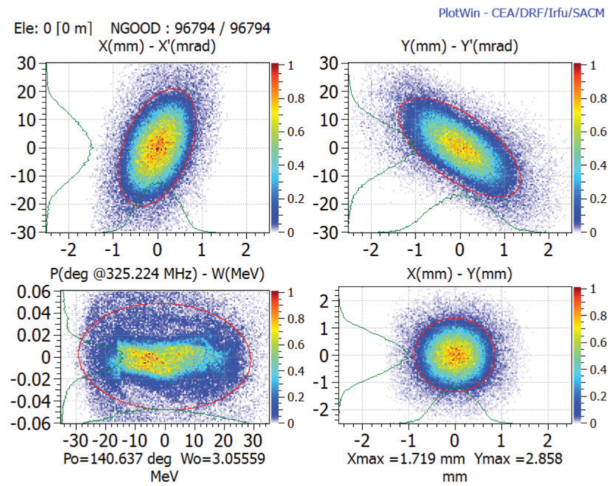

Figure 5: Phase-Space plots and distribution projections (green curves) at the RFQ exit in case of the modified m-shape. The colors of the scatter plots refer to the normalized (macro) particle density (cf. scales at the right frames of the plots). The red ellipses are associated to the normalized 90 % emittances.

Table 2: Beam Parameters at RFQ Exit

Parameter	original m	modified m
$\varepsilon_{x,out}$	0.36 π mm mrad	0.31 π mm mrad
$\varepsilon_{y,out}$	0.32 π mm mrad	0.33 π mm mrad
$\varepsilon_{z,out}$	0.44 MeV deg	0.28 MeV deg
$\alpha_{x,out}$	0.80	- 0.47
$\beta_{x,out}$	9.55 $\frac{cm}{rad}$	4.58 $\frac{cm}{rad}$
$\alpha_{y,out}$	- 0.63	0.85
$\beta_{y,out}$	4.92 $\frac{cm}{rad}$	10.20 $\frac{cm}{rad}$
W_{syn}	3.03 MeV	3.05 MeV
W_{ave}	3.03 MeV	3.06 MeV
$W_{syn} - W_{ave}$	- 6.50 keV	- 5.20 keV
$\frac{long.losses}{radial losses}$	2.54 %	1.91%
Transmission	93.02 %	96.79 %

CONCLUSION

The beam dynamics design was developed with the Code RFQGen in accordance with the source beam parameters as given by N. Chauvin and the design parameters of the Proton Linac at FAIR. The optimum number of cells in the radial matcher turned out to be 4. Modifying the shape of modulation parameter m within the first 90 cells reduced the x-emittance from 0.36 π mm mrad to 0.31 π mm mrad (required: 0.30 π mm mrad) and the longitudinal emittance from 0.44 MeV deg to 0.28 MeV deg (required: 0.35 MeV deg). The transmission increased from 93.02 % to 96.79 % and the number of cells from 332 to 335.

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