# Beam Dynamics for the FAIR p-Linac Ladder RFQ

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## Overview

After the successful measurements with a *0.8 m* prototype the construction of a *3.3 m* Ladder-RFQ at IAP, Goethe University Frankfurt, has been finished this summer. It is designed to accelerate protons from *95 keV* to *3.0 MeV* according to the design parameters of the p-Linac at FAIR. Along the acceleration section the parameters modulation, aperture and synchronous phase are linearly varied with cell number, which differs from former designs from IAP Frankfurt. The ratio of transversal vane curvature radius to mid-cell radial aperture as well as the vane radius itself are constant, which favors a flat voltage distribution along the RFQ. This was verified by the implantation of the modulated vane geometry into MWS-CST RF field simulations. The development of adequate beam dynamics was done in close collaboration with the IAP resonator design team. The RFQGen-code was used for beam dynamics simulations.

**Table 1:** RFQ parameters.

| Parameter | Value |
|---|---|
| Frequency | 325.224 MHz |
| Electrode Voltage | 88.43 kV |
| Kilpatrick Factor | 1.88 |
| $\rho^*/r_0^{**}$ | 0.85 |
| Electrode Length | 3329 mm |
| Number of RFQ cells | 245 |
| Number of RM cells | 5 |

**Table 2:** Input beam parameters.

| Parameter | Value |
|---|---|
| Entrance Energy | 95 keV |
| Output Energy | 3.015 MeV |
| Beam Current*** | 100 mA |
| Transversal $\varepsilon_{in,n,rms}$**** | 0.3 $\pi$ mm mrad |
| Entrance Particle Distribution | 4D Waterbag |
| Number of Macro Particles | 1.00E+05 |

*) Transverse radius of curvature of vane tip.

**) Mid-cell radius.

***) The design was optimized for an entrance current of 100 mA and checked for a variety of alternative entrance currents reaching all the way down to the zero-current case.

****) If not stated otherwise, all emittances presented in this poster are normalized rms emittances.

## Beam Dynamics Design

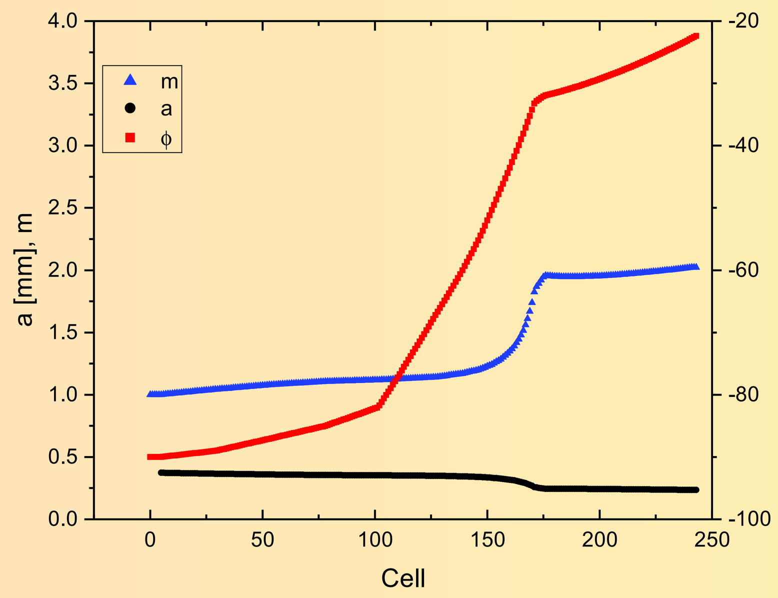


**Figure 1:** Parameter plots against the cell number.

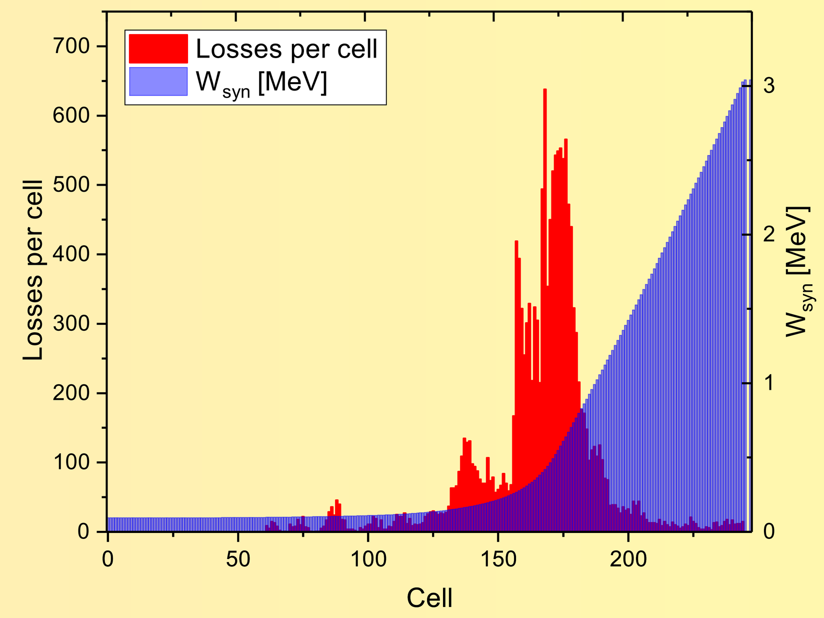


**Figure 2:** Particle losses per cell and synchronous energy along the RFQ at *100 mA* beam current.

Fig. 1 shows the plots of modulation parameter *m*, (minimum) radial aperture *a* and synchronous phase $\phi$ against the cell number. The acceleration section with linear parameter settings results in significantly reduced electrode lengths [1]. This design was inspired by the beam dynamics design of CERN's Linac4-RFQ [2], [3].

Fig. 2 shows the plots of the (quasi-)particle losses per cell and the synchronous energy $W_{syn}$ against the cell number as simulated by the RFQGen-Code [4]. The entrance beam current was *100 mA*. Most losses occur at the end of the gentle buncher section, i.e. at $W_{syn}$ = *0.67 MeV*. The losses in cells corresponding to a $W_{syn}$ above *1.4 MeV* are rather low (< *4.5%* of the overall losses). This is important, since higher energetic protons colliding with the electrodes could lead to cavity activation.

The ratio of overall longitudinal to transversal losses along the RFQ is approximately *0.59* at an accepted energy width of ±*5%* at the RFQ exit. The corresponding transmission is *84.6%* (cf. Fig. 3). However, with no energy window defined at the RFQ exit the total transmission amounts to *86.7%.*

References: [1] J. H. Billen, "RFQ Design Codes", Los Alamos Scientific Lab., NM (USA), 2005.
[2] C. Rossi et al., "The Radiofrequency Quadrupole Accelerator for the Linac4", Proceedings of LINAC08, Victoria, BC, Canada, p. 157.
[3] A. Lombardi et al., "END-TO-END BEAM DYNAMICS FOR CERN Linac4", Proceedings of HB2006, Tsukuba, Japan, p. 79.
[4] L. Young, J. Stoval, "RFQGen User Guide", Los Alamos Scientific Lab., NM (USA), 2017.

## RFQ Exit Distributions

| Parameter | Value |
|---|---|
| Entrance Beam Current | 100 mA |
| Transmission | 84.57% |
| Long. Losses / Trans. Losses | 58.68% |
| $W_{syn,out}$ | 3.015 MeV |
| $W_{ave,out}$ | 3.012 MeV |
| $\varepsilon_{x,out}$ | 0.3289 $\pi$ mm mrad |
| $\varepsilon_{y,out}$ | 0.3247 $\pi$ mm mrad |
| $\varepsilon_{z,out}$ | 0.2111 MeV deg |

**Table 3:** Beam parameters at the RFQ exit (*10 mm* behind the electrode ends) in case of an input beam current of *100 mA*. The synchronous end energy was set slightly (*0.5%*) higher than the required value of *3 MeV* to establish a safety margin, since the MEBT and DTL can handle this "overshooting" far better than "undershooting". Transversal emittance growth stayed below *10%*.

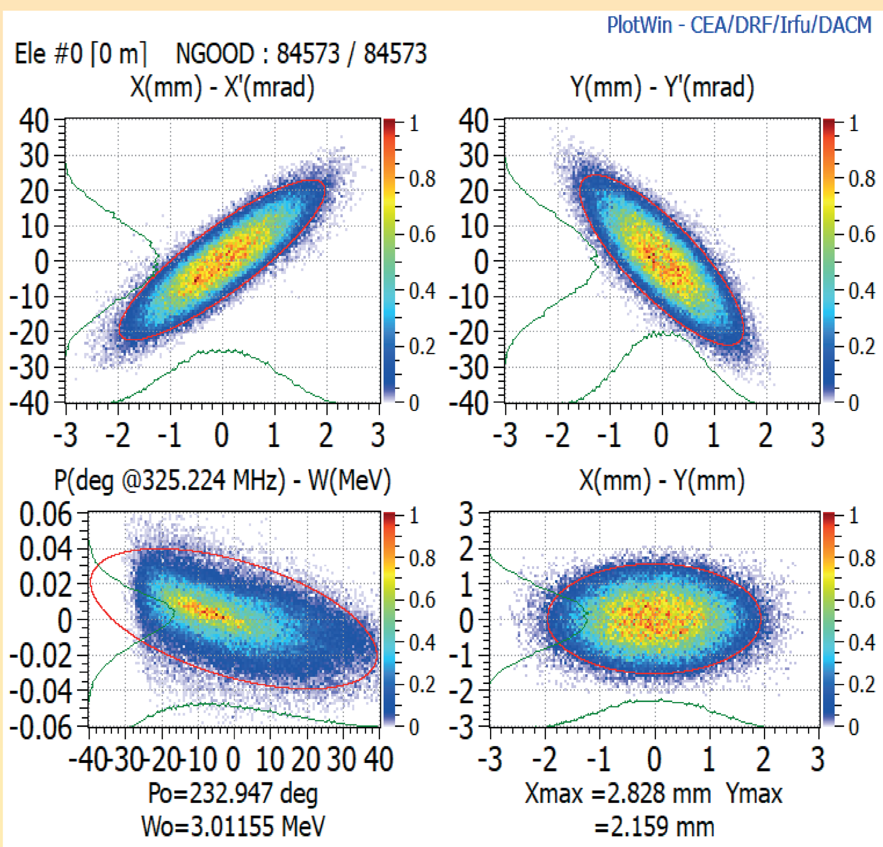


**Figure 3:** Phase-space plots and distribution projections (green curves) at the RFQ exit (*10 mm* behind the electrode ends) in the case of an entrance current of *100 mA*. The colors of the scatter plots refer to the normalized (macro) particle density (linear scales at the right frames of the plots). The red ellipses correspond to the *95%* emittances.

The used input distribution was a *4D Waterbag* distribution consisting of *1.0E+05* macro-particles.

## Initial Twiss Parameters Error Studies

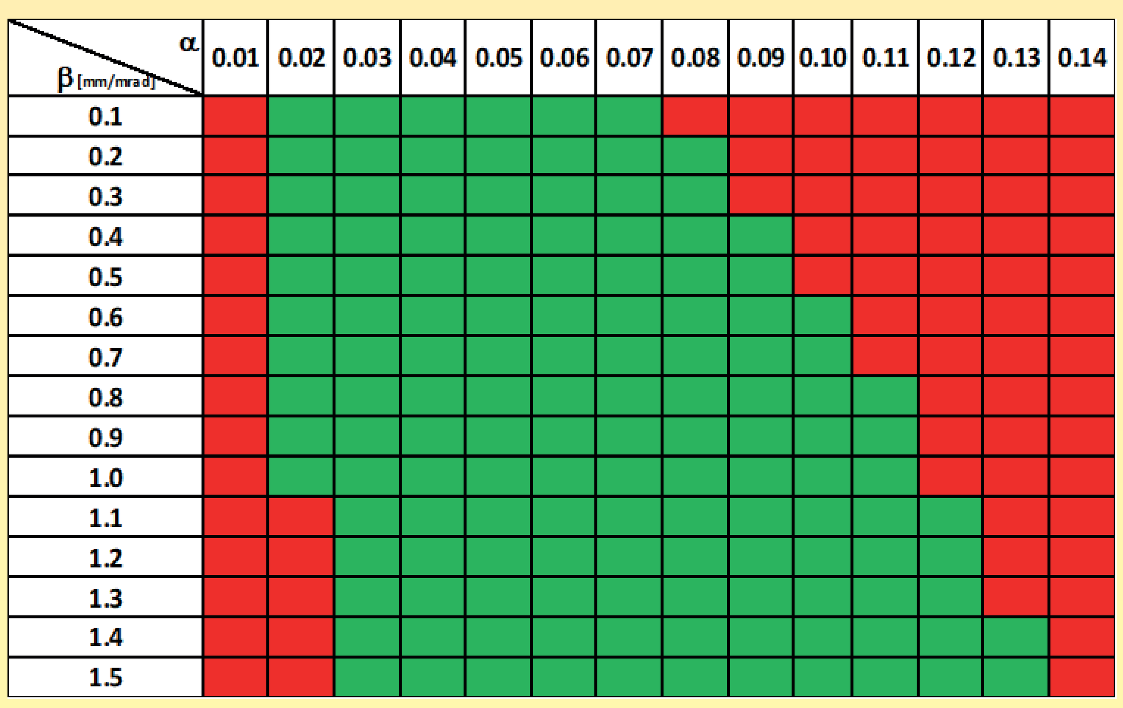


**Figure 4:** In order to check the beam dynamics' stability against deviations in the initial Twiss parameters $\alpha_{in}$ and $\beta_{in}$, a series of error studies was performed in RFQGen.

A combination of Twiss parameters was considered to lead to an output beam of sufficiently high quality (marked in green) if all of the following criteria were met:

- the transmission was at least *70%*
- each transversal output emittance $\varepsilon_{x/y}$ deviated not more than *+10%* from its nominal value of *0.3 $\pi$ mm mrad*
- the longitudinal output emittance $\varepsilon_z$ deviated not more than *+30%* from its nominal value of *0.235 MeV deg.*

It can be seen that the RFQ beam dynamics design is quite robust against deviations from the assumed set of initial Twiss parameters $\alpha_{in}$ = *0.7* and $\beta_{in}$ = *0.04 mm/mrad.*

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