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NEW BEAM DYNAMICS SIMULATIONS FOR THE FAIR p-LINAC RFQ

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Abstract

The construction of a 3.3 m Ladder-RFQ at IAP, Goethe University Frankfurt, has been finished successfully last summer. This RFQ is designed to accelerate protons from 95 keV to 3.0 MeV according to the design parameters of the p-Linac [1,2] at FAIR[1] [3]. Along the acceleration section the parameters modulation, aperture and synchronous phase are varied linearly with cell number, which differs from former designs from IAP Frankfurt. The ratio of transversal vane curvature radius to mid-cell radial aperture and the vane radius itself are constant. The development of an adequate beam dynamics design was done with the aid of the RFQGen-code and in close collaboration with the IAP resonator design team. The RFQ beam dynamics design could be successfully reproduced with the TOUTATIS-routine of CEAs[2] TraceWin-code. Several new beam dynamics simulations were performed on the design. Among these were current and Twiss parameter studies as well as simulations concerned with the investigation of longitudinal entrance and exit gap field effects [4]. Others were based on new measurements in the LEBT-line performed by the GSI[3] Ion Source Group in April 2019. In the near future, further LEBT measurements and subsequent simulations (among other to design a well-fitting cone for the RFQ), as well as mechanical error studies in TOUTATIS, will follow.

THE BEAM DYNAMICS DESIGN OF THE FAIR p-LINAC

The RFQGen-code [5] was used for generating the beam dynamics design of the 3.3 m Ladder-RFQ [6] (see Table 1). The current of the entrance beam was chosen rather high as 100 mA in order to have a large current margin. It was modeled with 10^5 (macro-)particles arranged in a 4D waterbag distribution as derived from beam measurements at CEA Saclay. Other than slightly undershooting the final energy, slightly overshooting poses no problem for the MEBT-section and the CH-DTL. For this reason and to provide a sufficient safety margin the final synchronous energy was set to 3.015 MeV. The almost linear behavior of modulation parameter m, (minimum) radial aperture a and synchronous phase ϕ against the cell number in the acceleration section results in higher acceleration efficiencies along the respective cells [7] and a therefore significantly reduced electrode length (compared to that generated by a more conservative design approach). This design was inspired by the beam dynamics design of CERN‘s Linac4-RFQ [8,9].

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Table 1: Beam Parameters at the RFQ Entrance and Electrode Design Parameters

Parameter	**Value**
Entrance Energy	95 keV
Beam Current	100 mA
Transversal $\varepsilon_{in,n,rms}$	0.3 π mm mrad
Frequency	325.224 MHz
Electrode Voltage	88.43 kV
ρ/r_0	0.85
Number of RM Cells	5

Table 2: Beam Parameters at the RFQ Exit (approx. 5 mm behind the Electrodes) for the Matched Case

Parameter	**Value**
$\varepsilon_{x,out,rms}$	0.33 π mm mrad
$\varepsilon_{y,out,rms}$	0.32 π mm mrad
$\varepsilon_{z,out,rms}$	0.20 π MeV deg
Synchronous Exit Energy W_{syn}	3.015 MeV
Average Exit Energy W_{ave}	3.012 MeV
Transmission	88.5 %

Reproducibility Check of the RFQ Beam Dynamics Design with TOUTATIS

The matched input case (cf. Table 2) was found with TOUTATIS [10] to occur for $\alpha = 1.5$ and $\beta = 0.06 \frac{mm}{\pi mrad}$ (cf. Fig. 3). These values were confirmed by the Twiss parameter studies with RFQGen (cf. next section). As can be seen in Fig. 1, both codes lead to very similar exit distributions. The normalized transversal emittances produced by the different codes deviated by approx. 5%, the longitudinal ones by ca. 10%.

INITIAL TRANSVERSAL TWISS PARAMETERS STUDIES WITH RFQGEN

In order to scan for pairs of suitable transversal Twiss parameters at the RFQ entrance, α_{in} was run from 0.1 to 2.5 with a step width of 0.1, whereas β_{in} was varied from 0.01 $\frac{mm}{\pi mrad}$ to 0.15 $\frac{mm}{\pi mrad}$ with a step width of 0.01 $\frac{mm}{\pi mrad}$. This resulted in 375 combinations of α_{in} and β_{in}. Since, unfortunately, the RFQGen-code itself does not include a sweep-function, a short workaround routine was coded with Python to automate the variation of the initial Twiss parameters. (All other beam parameters and all RFQGen settings remained constant during this simulation series.)

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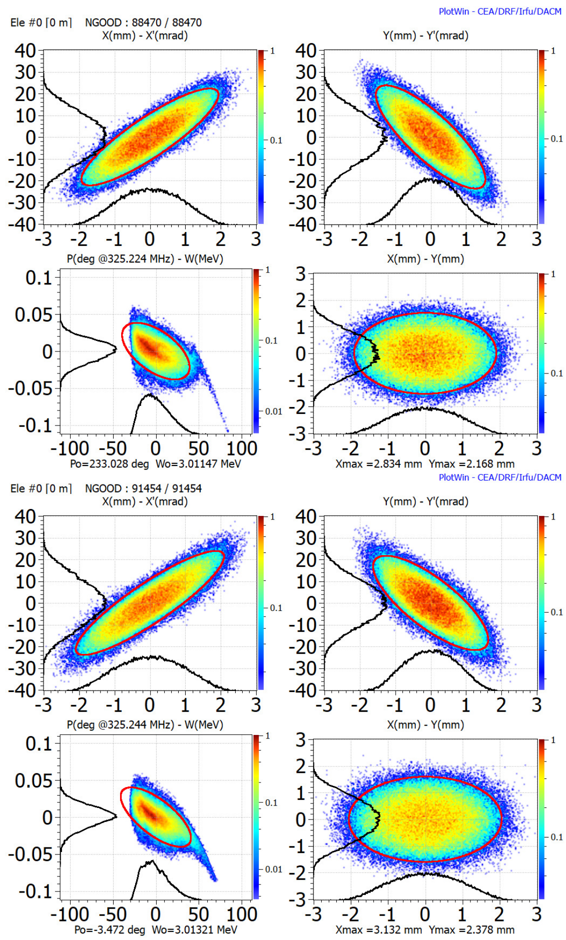

Figure 1: Direct comparison between the original RFQGen simulation results for the matched case (top) and the results of its reconstruction with TOUTATIS (bottom). Both codes lead to very similar RFQ exit distributions (approx. 5 mm behind the electrodes), which makes a strong case for the validity of the beam dynamics design. The colors of the phase-space plots refer to the normalized (macro) particle density (cf. scales at the right frames of the plots). The red ellipses correspond to the 95 % emittances, and the black graphs to the distribution projections.

A combination of Twiss parameters α_{in} and β_{in} was considered to lead to an output beam of sufficiently high quality if all of the following criteria were met:

- the transmission was at least 70 %
- each transversal output emittance $\varepsilon_{x/y}$ deviated no more than ± 10 % from its assumed value of $0.33\,\pi$ mm mrad
- the longitudinal output emittance ε_z deviated no more than ± 30 % from its assumed value of $0.235\,\pi$ deg MeV.

The results of this Twiss parameter studies are recorded in Fig. 3. For all fields colored other than white, the above criteria are met. It can be seen that the RFQ beam dynamics design is able to cope well with a variety of transversal initial Twiss parameters.

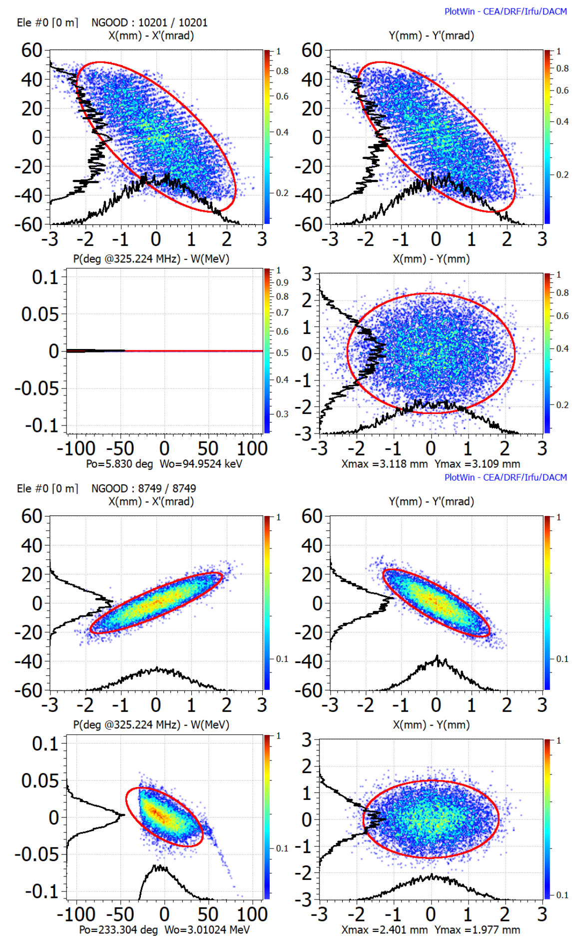

Figure 2: Phase space plots at the RFQ entrance (top) and exit (bottom). The measured distribution was tracked 260 mm (90% space charge compensated) with TraceWin to the RFQ entrance leading to $\alpha = 1$ and $\beta = 0.06\frac{mm}{\pi\, mrad}$ at this position. Legend cf. Fig. 1.

RFQGEN AND TRACEWIN SIMULATIONS BASED ON LEBT MEASUREMENTS

In April of 2019 new emittance measurements were performed by the GSI Ion Source Group at CEA Saclay. They took place ca. 240 mm after the second solenoid in the LEBT. These measurements served as the basis for LEBT-simulations with CEA's TraceWin-Code [11]. In TraceWin several of these distributions were tracked through the succeeding drift (90% SCC) in order to determine the position of their beam waists, i.e. the positions at which the RFQ entrance should be placed for each case and which were determined by the solenoid currents settings. One of the particle distributions at the RFQ entrance showed especially promising Twiss parameters close to that of the matched case. The respective RFQ exit distribution generated by

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β [mm/π mrad] / α	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	
0.1	52.20%	70.30%					71.07%	68.39%								**0.1**
0.2	53.47%	71.64%					72.33%	69.83%								**0.2**
0.3	53.51%	72.78%		78.92%				71.62%	68.61%							**0.3**
0.4	53.26%	73.79%	79.42%		79.53%				70.30%	66.90%						**0.4**
0.5	52.04%	74.27%				78.92%			71.67%	68.67%						**0.5**
0.6	50.62%	74.21%					78.06%			70.23%	66.89%					**0.6**
0.7	48.73%	73.80%					79.21%			71.38%	68.33%					**0.7**
0.8	46.35%	73.01%		85.16%				77.99%		72.38%	69.53%					**0.8**
0.9	43.99%	71.78%		85.69%	86.33%			79.13%		73.60%	70.49%	67.85%				**0.9**
1.0	41.51%	70.16%		85.83%	87.08%	**85.95%**			77.74%		71.66%	68.79%				**1.0**
1.1		68.25%		85.96%	87.73%	86.78%			78.57%		72.74%	69.84%				**1.1**
1.2		66.14%	79.62%	85.71%	88.14%	87.43%	85.34%		79.28%			73.81%	67.94%			**1.2**
1.3		63.41%	78.30%	85.03%	88.36%	88.34%	85.99%			77.61%		72.18%	69.06%			**1.3**
1.4		60.87%	76.51%		88.16%	88.45%	87.26%			78.41%			70.22%	66.95%		**1.4**
1.5		57.33%	74.81%		87.66%	**88.57%**	87.14%	85.14%		79.49%			70.73%	68.05%		**1.5**
1.6		54.07%	73.17%		86.71%	88.70%	87.79%	85.59%		79.98%			71.84%	68.60%		**1.6**
1.7		50.72%	70.91%		86.24%	88.52%	88.01%	86.31%			78.17%		72.54%	69.93%		**1.7**
1.8			68.43%	78.79%		87.62%	88.23%	86.87%			70.05%			70.57%	67.79%	**1.8**
1.9			66.01%	77.38%		87.18%	88.00%	87.10%			79.32%			71.67%	68.62%	**1.9**
2.0			62.95%	75.46%		86.51%	88.07%	86.93%	85.19%		79.97%			71.91%	69.38%	**2.0**
2.1			60.05%	73.68%		85.34%	87.28%	87.00%	85.47%			78.34%			70.41%	**2.1**
2.2			57.02%	71.58%	79.30%		86.69%	86.92%	85.44%			78.47%				**2.2**
2.3				69.02%	77.90%		85.93%	86.46%	85.29%			78.95%				**2.3**
2.4				66.81%	76.34%			85.83%	85.68%			79.54%				**2.4**
2.5				64.40%	74.32%	79.91%		85.33%	85.11%			79.68%				**2.5**
	0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**	**0.11**	**0.12**	**0.13**	**0.14**	**0.15**	

Figure 3: This chart provides an overview about the combinations of the initial Twiss parameters $\alpha_{trans,in}$ and $\beta_{trans,in}$. For combinations, that led to RFQ exit distributions considered insufficient, the fields were left white. The different colors refer as follows to the distinct transmission intervals: White: T < 70 %, Yellow: T = 70 % – 80 %, Moss green: T = 80 % – 90 %, Dark green: T = 85 % – 88 %, Blue: T > 88 %. For selected cases, the transmission values are explicitly stated.

Table 3: The values of $\alpha_{trans.,in}$ and $\beta_{trans.,in}$ were 1 and 0.06 $\frac{mm}{\pi mrad}$, respectively, for both distributions (cf. Fig. 3). All emittances are normalized RMS emittances.

Particle Distribution	Trans. Entr. ε	Current	Transmission	Trans. Exit ε	Long. Exit ε
Measured	0.23 π mm mrad	110 mA	85.8%	0.26 π mm mrad	0.21 π deg MeV
Generic	0.30 π mm mrad	100 mA	86.0%	0.33 π mm mrad	0.22 π deg MeV

an RFQGen simulation was compared to that of the corresponding case of above Twiss parameter studies (see Table 3). Figure 2 shows the RFQ entrance and exit distributions corresponding to the (as of now) optimum measured and tracked input case.

CONCLUSION

The beam dynamics design was developed with the Code RFQGen in accordance with both the source beam parameters as given by GSI and CEA Saclay and the design parameters of the Proton Linac at FAIR. The reconstruction of the beam dynamics design with TOUTATIS for the matched case led to very similar simulation results.

Future beam measurements after the second LEBT solenoid are needed – also for designing and constructing a well-fitting cone at the RFQ entrance. With a length shorter than 260 mm in the case discussed above and presented in Table 3 design and construction of such a cone will be challenging, but definitely seem feasible. It remains to be checked, whether the length of the cone could even be reduced further in order to provide the RFQ with entrance distributions whose Twiss parameters are even closer to those of the matched case.

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