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BEAM DYNAMICS FOR THE FAIR P-LINAC LADDER RFQ*

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Abstract

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 midcell radial aperture and the vane radius itself are constant to support a flat voltage distribution along the RFQ. This was verified by 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. Among those were also error studies, that were performed to test the beam dynamic's stability against input Twiss parameter deviations to a degree indicated by the LEBT measurements performed in Q1/2018 at CEA[1] Saclay with participation of GSI's[2] Ion Source Group.

BEAM DYNAMICS DESIGN

The RFQGen-code was used for the beam dynamics calculations [1]. The beam dynamics design determined the mechanical design of the RFQ electrodes and was arrived at in consideration of the source beam as given by the Ion Source and LEBT Group of CEA Saclay and the design parameters of the Proton Linac at FAIR [2] (see Table 1). The current of the entrance cw beam was chosen rather high to 100 mA in order to have a large current margin. It was modeled in RFQGen with 10^5 (macro-)particles arranged in a 4D waterbag distribution. Other than slightly undershooting the final energy, slightly overshooting it 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. Figure 1 shows the plots of modulation parameter m, (minimum) radial aperture a and synchronous phase ϕ against the cell number. Their almost linear courses in the acceleration section result in higher acceleration efficiencies along the respective cells [3] 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 [4, 5].

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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
Twiss Parameter $\alpha_{x/y,in}$	0.7
Twiss Parameter $\beta_{x/y,in}$	0.04 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 Wxit (10 mm behind the end of the electrodes)

Parameter	Value
$\varepsilon_{x,out,rms}$	0.33 π mm mrad
$\varepsilon_{y,out,rms}$	0.32 π mm mrad
$\varepsilon_{z,out,rms}$	0.21 MeV deg
Synchronous Exit Energy W_{syn}	3.015 MeV
Average Exit Energy W_{ave}	3.012 MeV
$W_{syn} - W_{ave}$	3 keV
$\frac{long.losses}{radial\,losses}$	59 %
Transmission	84.6 %

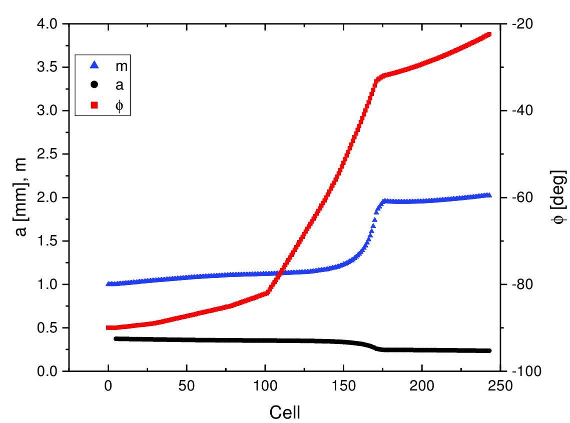

Figure 1: The modulation parameter, m, (minimum) radial aperture a and synchronous phase ϕ against the cell number.

Figure 2 shows the plots of the (macro-)particle losses per cell and the synchronous energy W_{syn} against the cell number as simulated by the RFQGen-Code. Most losses occur at the end of the gentle buncher section, i.e. at W_{syn} = 0.67 MeV. Here, the longitudinal losses reduce the longitudinal emittance, which did grow significantly during the earlier

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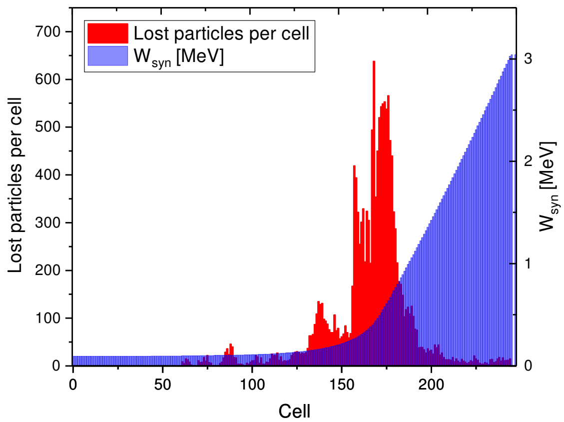

Figure 2: Courses of particle losses per cell (red) and the synchronous energy W_{syn} (purple) against the cell number. The number of entrance (macro-)particles was set 10^5.

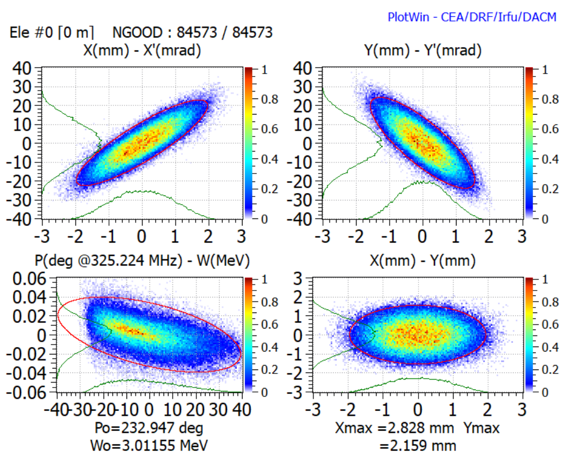

Figure 3: Phase-space plots and distribution projections (green curves) at the RFQ exit (10 mm behind the electrode ends). The entrance current was chosen to 100 mA. The colors of the scatter plots refer to the normalized (macro-) particle density (cf. scales at the right frames of the plots). The red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

stages of the bunching process, to reach saturation in a value close to that at the end of the shaper section. The losses in cells corresponding to a $W_{syn} > 1.42$ MeV are rather low ($<4.5\%$ of the overall losses). This is important since protons with energies above 2 MeV colliding with the electrodes could lead to cavity activation. The ratio of overall longitudinal to transversal losses along the RFQ is approximately 0.59 (cf. Table 2) with the reduction of beam current due to longitudinally lost particles (i.e. the particles, which‘s energies differ from W_{syn} more than a sensibly set threshold) amounting to 5.7 mA. The RFQGen-Code does not track how many of the longitudinally lost particles actually still traverse the RFQ. Therefore, the beam current at the RFQ exit might actually be as high as 90.3 mA (= 84.6 mA+5.7 mA) instead of 84.6 mA(cf. Table 2). This was taken into consideration for LORASR-simulations [6] concerning the MEBT-section and the CH-DTL performed at IAP. However, if the allowed difference between a given particle's energy and W_{syn} (i.e. the threshold, that defines if a particle is lost longitudinally) is set unreasonably high (here: almost to the value of the final design energy), transmission is raised to only 86.7 %, i.e. only increased by 2.1 %.

Effects of the Longitudinal Fringe Fields

Because of the unequal potential of adjacent electrodes of 4-ROD RFQs a non-zero longitudinal fringe field exists between the grounded tank and the net potential of the electrodes at the RFQ entrance as well as the exit [7]. If the transient-time factor is taken into account the longitudinal fringe field causes an energy modulation of up to ± 2 keV at the RFQ entrance. The small pre-bunching effect of the longitudinal electric field in the entrance gap of the RFQ on the incoming cw beam will be used to benefit the beam dynamics. At the RFQ exit the ratio between the gap length and the cell length $l = \beta\lambda/2$ is approximately 0.3. Accordingly, the transient time factor approaches one. Depending on the synchronous phase the total effect to the beam energy results to ± 30 keV.

Figure 3 shows the phase-space plots and distribution projections at the RFQ exit in case of the original energy threshold, i.e. one that was chosen reasonably high.

LEBT MEASUREMENTS

In Spring 2018 emittance measurements were performed at CEA Saclay, whereby the Twiss parameters were also determined. They took place after the first solenoid in the LEBT. Theses measurements served as the basis for LEBT-simulations with CEA's TraceWin-Code [8], which led to more realistic values for the Twiss parameters and emittances at the RFQ entrance.

Error Studies

Since the LEBT measurements suggested that the initial Twiss parameters α_{in} and β_{in} might deviate somewhat from their design values (cf. Table 1), error studies were performed with RFQGen. α_{in} was run from 0.1 to 1.5 with a step width of 0.1, whereas β_{in} was varied from 0.01 $\frac{mm}{mrad}$ to 0.14 $\frac{mm}{mrad}$ with a step width of 0.01 $\frac{mm}{mrad}$. This resulted in 210 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.

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 π mm mrad
- the longitudinal output emittance ε_z deviated no more than + 30 % from its assumed value of 0.235 MeV deg.

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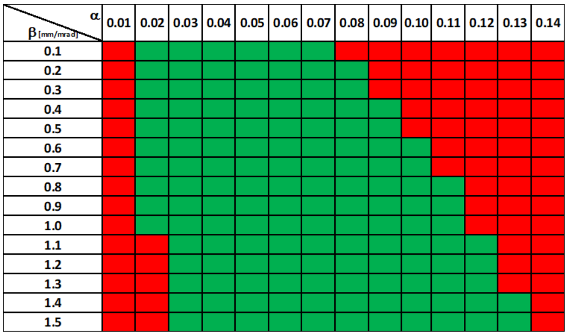

Figure 4: This Matrix provides an overview over the combinations of the initial Twiss parameters α_{in} and β_{in}, that did (green) and did not (red) lead to what were considered to be exit beams of sufficiently high quality.

Figure 4 shows a matrix, in which the results of the error studies are recorded. It can be seen that the RFQ beam dynamics design is able to cope well even with larger deviations from the assumed initial Twiss parameters.

CONCLUSION

The beam dynamics design was developed with the Code RFQGen in accordance with the source beam parameters as given by the Ion Source and LEBT Group of CEA Saclay and the design parameters of the Proton Linac at FAIR. It was inspired by the beam dynamics design of CERN's Linac4-RFQ. Considering the high design current of 100 mA, the desired parameters at the RFQ exit are met remarkably well. Furthermore, the error studies performed on the input Twiss parameters showed that even larger deviations from the design Twiss parameters can be tolerated by the RFQ.

Not only can the effects of the longitudinal fringe fields at the RFQ entrance and exit be coped with well, they even can be used to lead to improved beam dynamics.

In the near future, new TraceWin and RFQGen simulations based on the results of the soon to be conducted measurements behind the second solenoid of the LEBT-line will be performed. In addition, possible effects of mechanical errors and displacements on the beam dynamics will be investigated with CEA Saclay's TOUTATIS-code [9].

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