BEAM DYNAMICS SIMULATION IN A FOUR - ROD RFQ

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Abstract

Beam dynamics simulations in a 4-rod RFQ structure have been carried out including nonideal field distribution and alignment errors. The field distribution has been calculated by the computer codes MAFIA and KOBRA. The computational results are in good agreement with beam measurements at the UNILAC 4-rod RFQ structure. It was shown that the misalignment of the electrodes above $\pm$ 0.2 mm reduced the RFQ transmission considerably, the intrinsic dipole field components also degrade the transmission.

Introduction

This work was initiated by the commissioning of the new high charge state injector at GSI, which consists of a 4-rod RFQ structure followed by an IH structure [1],[2]. Beam measurements at the RFQ structure indicated that the transmission of the injected beam at the design input emittance was below 50 %, full transmission was calculated if an ideal quadrupole field is assumed. Two possible sources of the field distortions will be considered. Due to the arrangement of the electrodes and the supporting stems, intrinsic field distortions occur even under the assumption of ideal alignment of the field generating electrodes. The second class considers field distortions by misalignment of stems and electrodes.

Field Calculations

The arrangement of electrodes and stems in the 4-rod RFQ are shown in Fig. 1 schematically. The four electrodes are supported by stems which are not symmetrically arranged arround the electrodes, all 18 stems are fixed at one base plate. Every electrode is only supported at every second stem. The intrinsic field distortions have been calculated by the MAFIA code and then described by the Fourier series:

$$U = \frac{V}{2}\sum_{n=1}^{\infty}\left(\frac{r}{r_0}\right)^n (a_n \sin n\varphi + b_n \cos n\varphi) \qquad (1)$$

where V is the voltage between adjacent electrodes; r_0 – mean aperture radius of the electrodes; r and φ - polar coordinates.

The coefficients of the series were calculated at the stem locations. Their values are:

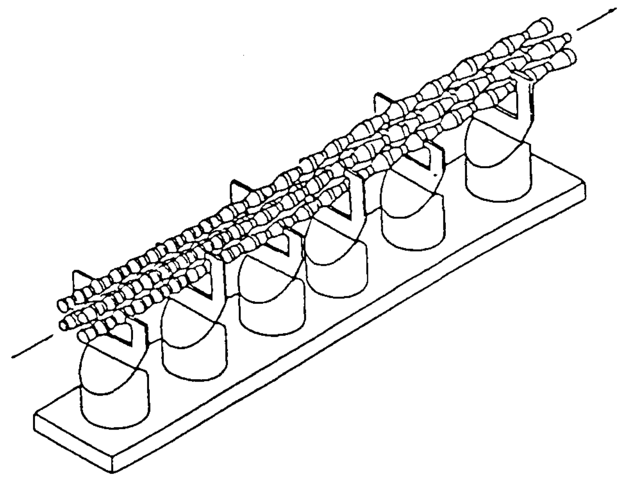

Figure 1: Arrangement of electrodes and stems in the 4-rod RFQ

$$\begin{aligned} a_1 &= 0.020 \\ b_1 &= 0.043 \\ a_2 &= 0.91 \\ a_6 &= 0.01 \\ a_{10} &= 0.009 \end{aligned}$$

The coefficients a_1, b_1 represent dipole components of the focusing field for horizontal and vertical planes correspondingly, a_2 is the coefficient of the quadrupole field.

Misalignment of the stems and electrodes were included in the calculations in the following way: It is assumed that there are errors in the positioning of each stem, a random distribution with a maximum error δ will be calculated. The electrodes are treated as straight lines between two stems. It follows that the electrical axis consists of sections of straight lines. The axis does not coincide with the optical axis, but the perfect quadrupole field distribution will be kept. For the beam dynamics simulations the corresponding displacement of the axis were added to the particle coordinate in each RFQ cell.

Distortions of the quadrupole symmetry of the electrodes by misalignment were calculated by the 3D code KOBRA. The field was calculated for an electrode system with 2 electrodes at their design position, one electrode is shifted by ΔR_x for the electrode of the x-plane and ΔR_y for the y-electrode. The results of extensive field calculations are represented as linear functions for the coefficients of the Fourier series defined by equation 1:

$$
\begin{aligned}
b_1 &= 1.9425\Delta R_x \\
a_1 &= 1.9425\Delta R_y \\
a_2 &= -1.08939\,(\Delta R_x + \Delta R_y) + 1 \\
b_3 &= -0.44899\Delta R_x \\
a_3 &= -0.44899\Delta R_y
\end{aligned}
$$

The beam dynamics simulations were carried out with the GSI PARMTEQ version. It has been changed in order to calculate the beam dynamics with the above described distorted electric fields.

Results of Simulations

The first three figures demonstrate qualitatively the effects of the different field distortions. A small input emittance was chosen.

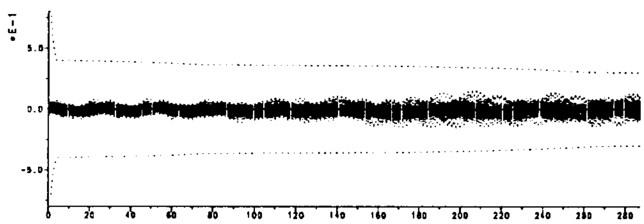

Figure 2: Particle distributions in X – plane along the structure. (Real field without misalignment).

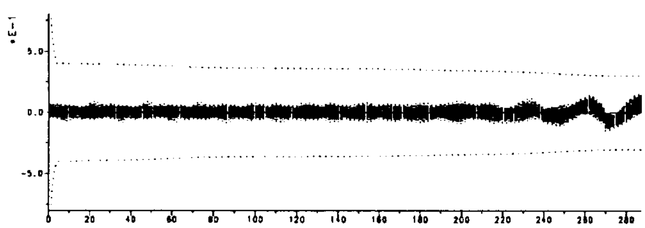

Figure 3: Particle distributions in X – plane along the structure. (Ideal field and alignment errors with maximum electrode displacement of ±0.2 mm).

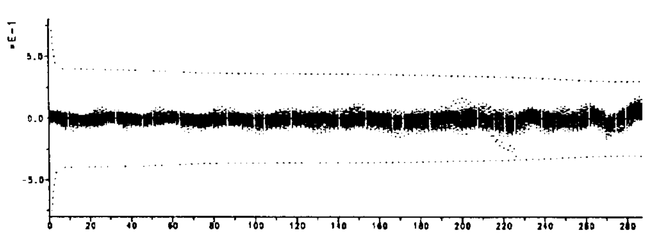

Figure 4: Particle distributions in X – plane along the structure. (Alignment errors with maximum electrode displacement of ±0.2 mm and real field distribution).

Fig. 2 shows the particle distribution if the quadrupole field is distorted due the design of the RFQ. Due to the inherent dipol fields the beam developes coherent oscillatons from the beginning of the structure, the emittance increases. In Fig. 3 the influence of stem displacements is shown. In the beginning only small oscillations are excited, at the end of the structure the amplitude of the coherent oscillation increases. The reason for this behavior is due to the fact that the number of cells between two stems is different: 20-25 cells at the beginning, 2-3 cells at the end. Thus the displacement of the axis of each focusing period is larger at the end. Both effects are combined in Fig. 4.

In the following diagrams the influence of field errors will be characterized by the dependence of the beam transmission on the input emittance. This curves can be compared with the results of beam measurements.

Fig. 5 shows the influence of alignment errors, but the ideal quadrupole field is maintained in these calculations. The reduction of transmission is evident: at the design input emittance of 200 mm·mrad the transmission decreases to 70 % at alignment errors of $\delta \leq 0.3mm$, to 40 % at $\delta \leq 0.4mm$.

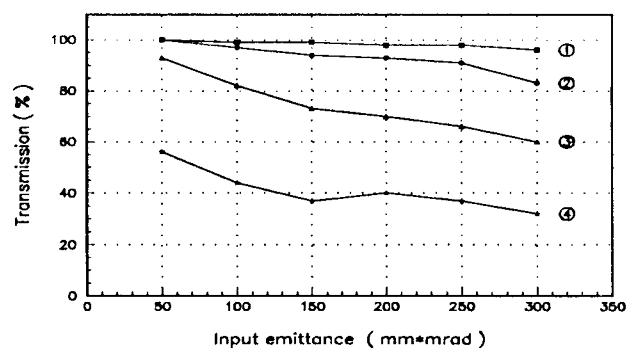

Figure 5: HLI RFQ transmission calculated with ideal quadrupole field. **1** - no alignment errors; **2** - alignment errors $\delta \leq 0.2$ mm; **3** - alignment errors $\delta \leq 0.3$ mm; **4** - alignment errors $\delta \leq 0.4$ mm.

The cases shown in Fig. 6 are more realistic: the distortion of the ideal quadrupole field caused by inherent design features and alignment errors are included. The above listed sets of coefficients are used for the computations. The influence of field distortions due to the design of the structure is shown with curve 3. A reduction to a transmission of 80 % at the input emittance of 200 mm·mrad was calculated. A further reduction of the transmission due to additional misalignment will occur with alignment errors above $\delta = 0.2mm$.

In Fig. 7 the experimental results are shown. Curve 1 describes the situation measured during the commissioning of the RFQ accelerator. An inspection of the electrode alignment was made, errors of electrode position up to 0.5 mm were measured [1],[3]. If we compare curve 1 of Fig. 7 with curve 5 of Fig. 6, the agreement is good. After a redesign of the RFQ electrodes [4] to allow a more accurate

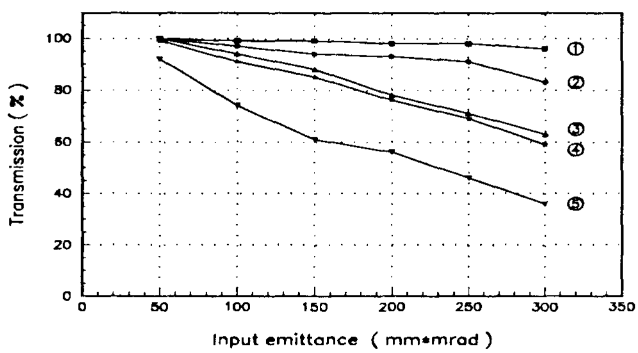

Figure 6: Calculated HLI RFQ transmission. **1** - ideal quadrupole field; **2** - ideal quadrupole field with alignment errors $\delta \leq 0.2$ mm; **3** - real field distribution without alignment errors; **4** - real field distribution with alignment errors $\delta \leq 0.2$ mm; **5** - real field distribution with alignment errors $\delta \leq 0.5$ mm.

alignment of the electrodes, the measured transmission is shown in Fig. 7, curve 2. The alignment error is near 0.1 mm now. Curve 3 of Fig. 6 describes the experiments very well. Due to our computations and measurements we can state, that the field generating electrodes should be aligned with an accuracy near ± 0.1 mm, field distortions generated by the design of the RFQ should be avoided, at least minimized.

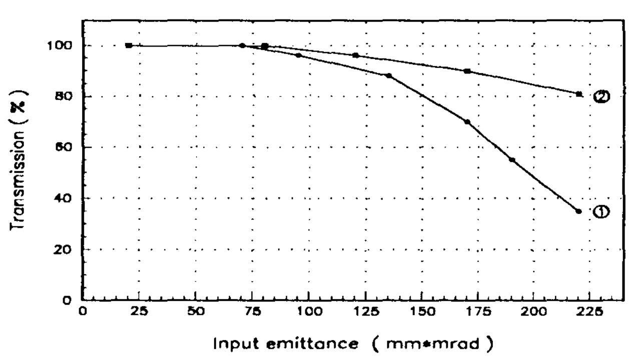

Figure 7: Experimental HLI RFQ transmission as a function of the input beam emittance (unnormalized). **1** - before alignment, measured error $\delta \sim 0.5mm$; **2** - after realignment, $\delta \sim 0.1mm$.

Conclusion

More realistic field distributions and misalignment of field generating electrodes can explain the performance of the GSI 4-rod RFQ. Both, design features and misalignment cause the deterioration of the acceptance. The well aligned structure has now a transmission of above 80 % at the design input emittance. A reduction of the dipole components should improve the transmission.

References

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