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BEAM PHYSICS ANALYSIS OF THE ESS RFQ NON-CONFORMITIES

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Abstract

The study proposes to expand the method to treat the voltage errors presented in [1], in which the deviation from the theoretical parameters is represented by a sum of periodic functions of z, to the machining errors and to take also into account positioning and alignment errors in the RFQ. This is a novel approach to study the RFQ errors which can also be used to treat the non-conformities during the fabrication process.

INTRODUCTION

During the fabrication of a Radio-Frequency Quadrupole (RFQ), deviation from the theoretical geometry, given by the beam dynamics and RF designs, may occur. This is the result of the machining process, brazing and assembly of the different parts. The quality of the final alignment of the RFQ in the tunnel will also affect the beam dynamics. In addition to what we may call geometry errors, the inter-vane voltage may differ from the optimal one due to the non perfect compensation of the mechanical errors by the slug tuners.

The treatment of the RFQ non-conformities from a beam dynamics point of view should include the above mentioned RFQ geometry and voltage errors. In this paper will be described a novel method to simulate the RFQ errors whose main objectives are:

1. to predict the beam dynamics and set tolerances;
2. to take into account data from 3D mechanical analysis and bead-pull measurements at different steps of the manufacturing process;
3. to have a realistic beam physics model of the RFQ when the latter is fabricated and qualified.

After a description of the method, we will apply the latter to the European Spallation Source (ESS) RFQ [2]. The ESS RFQ is a 352.21 MHz 4-vanes RFQ composed of 5 sections of roughly 90 cm each. Requirements on the tolerances for the ESS RFQ are reported in Tab. 1. Plans to treat the non-conformities of the ESS RFQ during fabrication will finally be presented.

METHODOLOGY

Voltage Errors

Each component of the error voltage vector $\Delta U(\Delta U_Q, U_S, U_T)$ is expressed as a sum of periodic functions of z:

$$\Delta U_i = \sum_{n=0}^{15} A_n \cos\left(\frac{n\pi z}{L_{\mathrm{RFQ}}} + \phi_n\right) \quad (1)$$

Table 1: Mechanical and Voltage Requirements

Parameter	Requirement
Machining	$< 20\ \mu$m
Vane positioning	$< 30\ \mu$m
Section positioning	$< 20\ \mu$m
RFQ alignment	$< 100\ \mu$m
Voltage error	< 2 %

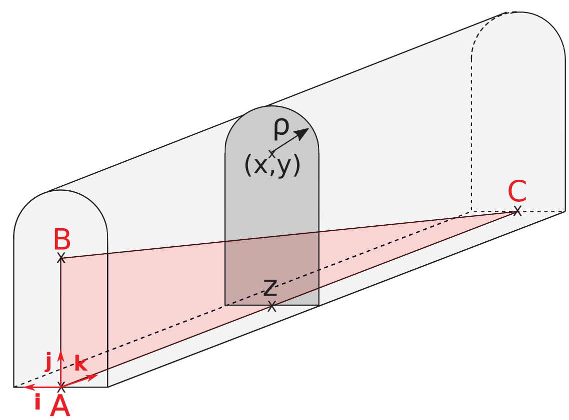

Figure 1: Vane tip geometry representation.

See [1] for more details on the expression of the voltage components.

Machining Errors

For each vane of the RFQ, the geometry of the tips can be described by the vector $X(x, y, \rho)$ in a specific frame attached to the vane as can be seen in Fig. 1. Machining errors, $\Delta X(\delta x, \delta y, \delta\rho)$ are, similarly to the case of the voltage, modelled by a continuous function of z:

$$\Delta X_i = \sum_{k=0}^{N} A_k \cos\left(\frac{k\pi z}{L_{\mathrm{vane}}} + \phi_k\right) \quad (2)$$

Positioning and Alignment Errors

Three points (A, B, C) are fixed on the vanes as can be seen in Fig. 1. Once four vanes have been brazed to form a section, the report of the measured coordinates of the set (A, B, C) in the corresponding section frame is given. This allows to express the real position of the vane tips taking into account the quality of the brazing. Such a procedure is applied on the five sections once they have been assembled to form the RFQ. The coordinates of the section fixed points are then given in the RFQ frame. Finally the impact of the final assembly of the RFQ in the tunnel is also considered. The methods permits to treat all geometry errors independently.

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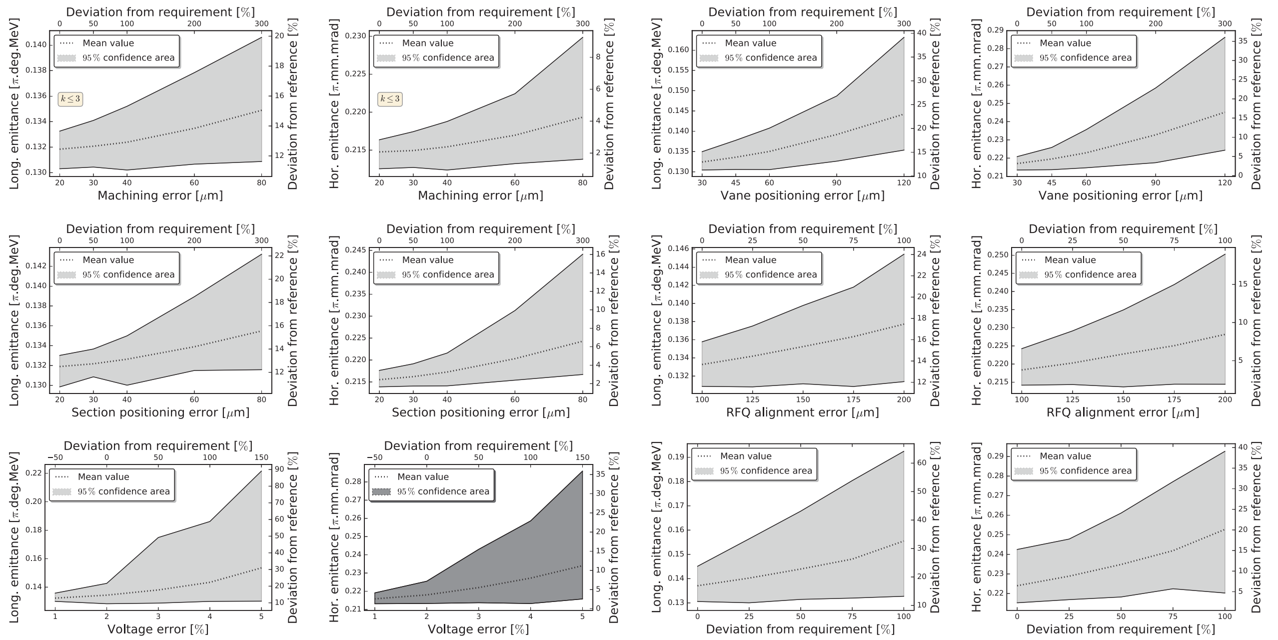

Figure 2: Results of the single and combined error study.

ERROR STUDY

Input Parameters and Hypotheses

For each case presented in the following, a set of 1 000 simulations have been launched with Toutatis [3]. A 70 mA input proton beam of 100k particles perfectly matched into the RFQ has been considered. The term reference is used for the RFQ output beam without errors.

It has been assumed that, at least at one abscissa z, the machining error and the voltage error reach their maximum corresponding amplitude. Similarly, when the vertexes of the triangle ABC are placed within in a cube of errors whose side is $2\delta r$, δr being the maximal displacement with respect to the perfect positioning, at least one vertex lies on one of the cube faces.

We limit here to the presentation of the longitudinal a horizontal emittances. The impact on other parameters of interest like the transmission is very small and not relevant on the amplitude range of the considered errors. However, significant beam radial shift and kinetic energy deviation have been observed for large amplitude of voltage errors.

Single and Combined Errors

In Fig. 2 are summarized the results of the RFQ error study for each single error and for the combined errors (last 2 plots). The single errors are machining, vane positioning, section positioning, RFQ alignment and voltage.

An increase of 10 % and 20 % emittance increase respectively in the longitudinal plane and the transverse plane is expected on average if the requirements are fulfilled. The vane positioning and the voltage errors are the main contributors to the degradation of the beam quality.

Influence of the Parameter k

In the results previously presented, the parameter k seen in Eq. 2 which represents the "frequency" of the error oscillation, has been limited to 3. This is considered reasonable to model the behavior of the milling cutter over the 90 cm length vane. However, larger values of k have been studied as reported in Fig. 3 where one can see the evolution of the average emittances as a function of the error amplitude.

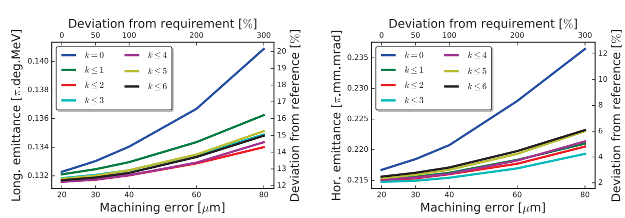

Figure 3: Influence of the parameter k.

Influenceof the Location of the Errors

We have isolated some geometry errors in a given section of the RFQ to characterize the sensitivity of the beam dynamics to the location of the errors. Results are presented in Figs. 4, 5 and 6 for the errors on the machining, vane positioning and section positioning respectively.

In addition to the "relatively" minor impact on the beam dynamics for the machining and the section positioning errors, there is no clear dependency on the the section number. Similarly for the vane positioning, which had a strong effect on the beam dynamics previously, not only can't we find a clear dependency on the section number but also the effect is significantly lower than for the displacement in all sections at the same time.

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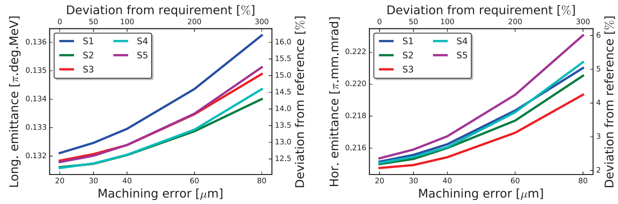

Figure 4: Influence of the vane machining within a specific section.

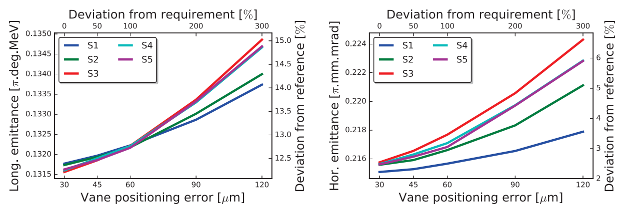

Figure 5: Influence of vane displacement in a given section.

PLAN TO TREAT THE NON-CONFORMITIES

Although no experimental data from 3D metrology measurements have been injected in the model yet since the RFQ vanes are currently being machined, we will describe in the following how we plan to treat the non-conformities during the RFQ fabrication process.

Reporting the Non-conformities

The report of the machining errors should contain the center, (x, y), and the average radius of the tip curvature, ρ, as indicated in Fig. 1. It is planed to sample the measurements of the latter parameters along the z-axis every millimeter. From the discrete collection of the tip parameters, we will obtain a continuous description of the vane tips by applying a fit function of the form described in Eq. 2. We can therefore obtain a description of the vane tips suitable for the beam dynamics calculations. In order to evaluate the amplitude of the machining errors, models of the vanes are built with the VTK format [4] and ParaView [5] is used as a visualization toolkit (See Fig. 7).

The report of the positioning quality should contain the coordinates of the fixed points in the appropriate frame of reference. Shift and rotation of the mechanical object with respect to its theoretical position will then be evaluated

Example

As an example, we have generated the geometry of the vanes in the 5th section the RFQ assuming that the machining and vane positioning reports are know and show maximum amplitude errors of 60μm for both parameters. Figure 7 shows a typical output of the machining error analysis. In Fig. 8 is reported the beam physics analysis: case A shows the result of the previous error study without taking into account the data , B takes into account the measurements data but keeps the requirements reported in Tab. 1; C adjusts

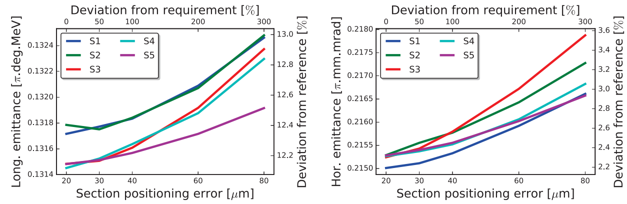

Figure 6: Influence of a given section displacement.

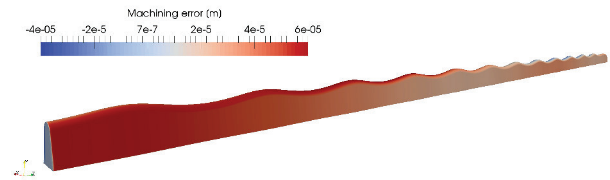

Figure 7: A typical output of machining errors analysis.

the geometry requirements to all vanes D adjusts the voltage requirements to $< 4\,\%$ (we have assumed that the voltage error is simply a linear function of the total vane displacement excluding the RFQ alignment); E adjusts both.

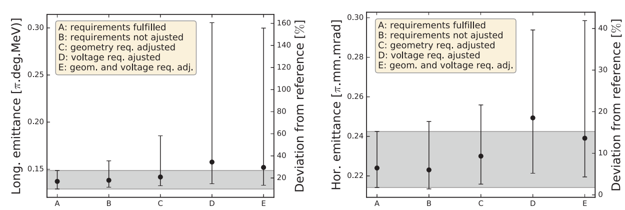

Figure 8: Results of the beam dynamics analysis (Error bars show 95 % confidence).

CONCLUSION

A beam physics model capable of treating independently errors of machining, vanes and sections positioning, RFQ alignment and voltage has been built. It uses periodic and continuous functions of z to describe the machining and voltage errors. It can also take into account the non-perfect positioning of the vanes, section and the entire RFQ independently by recording the coordinates of a set of three fixed points on each main mechanical component of the RFQ.

The model not only gives a novel approach for the study of the RFQ errors but it is also planed to use it as a verification tool for the beam dynamics quality during the RFQ fabrication process.

However, the model has not yet been tested with real measurements data coming from the 3D metrology characterization of the RFQ geometry or the results of the voltage characterization with the bead-pull technique. In particular the modelization of the RFQ vane tips by the functions of Eq. 2 should be validated. The assumption of the RFQ being a perfect rigid body should also be challenged since the cavity might experience deformation due to its own weight.

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