PREDICTABILITY OF THE BEAM QUALITY DURING RFQ VOLTAGE TUNING

A. Ponton*, European Spallation Source ERIC, Lund, Sweden
Alain. C. France, CEA/DRF/IRFU, Saclay, France

INTRODUCTION

As described in a previous study [1], the voltage in a 4-vanes RFQ can be expressed by a vector containing three components: $U = (U_Q, U_S, U_T)$ where U_Q is the quadrupolar component and U_S and U_T are two dipolar components. In the absence of geometry errors and for the accelerating mode, the vector is simply $U = U_0 = (V_p, 0, 0)$ with V_p the theoretical inter-vane voltage given by the beam dynamics. The voltage becomes in the presence of manufacturing imperfections: $U = U_0 + \Delta U$ with $\Delta U = (\Delta U_Q, U_S, U_T)$. Tuners equally spaced along the RFQ (15 per quadrant in the case of the ESS [2]) aim at reducing the voltage error to an acceptable level thus preserving the quality of the output beam. Nevertheless the voltage errors will not vanish completely and it was assumed than each component of ΔU can be expressed as [1]:

$$\Delta U_i = \sum_{n=0}^{15} A_{i,n} \cos \frac{n\pi}{L} z \qquad i = Q, S, T \tag{1}$$

with n the harmonic number, $A_{i,n}$ the amplitude of the error (positive or negative), L the RFQ length and z the coordinate on the beam axis. The study showed that higher harmonics were particularly dangerous for the beam quality. To illustrate this point, the effects of single harmonic errors on the longitudinal emittance, ϵ_ℓ, and on the $4D$ transverse emittance, ϵ_t, are depicted respectively in Figs. 1 and 2 for $|A_n|/V_p$ ranging from 1 % to 5 %. It was suggested finally that not only the amplitude of the voltage errors but also their spacial frequency should be taken into account during the RFQ tuning phase.

In the present paper, we propose to continue and enrich the previous analysis by answering the two following questions:

1. What is the impact on the beam dynamics when the voltage vector can be expressed by a limited number of harmonics?

2. Can the knowledge of the effects of single harmonic errors predict the effects of the real RFQ voltage?

Even if the study covers more parameters, we will limit ourselves to the presentation of ϵ_ℓ and ϵ_t due to the brevity of this report. All the simulation results presented below have been obtained with Toutatis [3]. The ESS RFQ [4] has served as model for this study.

* aurelien.ponton@esss.se

[1] Note that the dependency in $\omega_0 t$, where ω_0 is the angular frequency of the accelerating mode is assumed and omitted in the present notation.

LIMITED SUM OF HARMONICS

We have considered that the voltage error components can be expressed by a limited number of harmonics that we refer to harmonic content. For example, for a harmonic content of 2, Eq. 1 reduces to:

$$\Delta U_i = A_{\alpha_i} \cos \frac{\alpha_i \pi}{L} z + A_{\beta_i} \cos \frac{\beta_i \pi}{L} z \tag{2}$$

where α_i and β_i are integers between 0 and 15 but $\alpha_i \neq \beta_i$.

We have randomly generated the amplitude, A_n, of each harmonic on a given set of selected harmonic numbers (themselves picked up randomly) for harmonic contents ranging from 1 to 10. The maximal error for each component has been limited such as $|\Delta U_i|/A_n$ is kept between 0 and M for $M \in [1, 2, 3, 4, 5]$ %. Having simulating 1 000 cases for each set of errors, this leads to a total of 50 000 RFQ voltage simulations (1 000 cases × 10 harmonic contents × 5 sets of maximal errors). Figures 3 and 4 summarize the study for harmonic content 3 as an example. The figures should be read as follows: when the voltage error can be be expressed mainly on 3 harmonics, there is 90 % probability that if the total error is less than 2 % then both the longitudinal and the transverse emittances increases will be limited to ∼ 6 % with respect to the case without errors. If we look at Figs. 5 and 6, where the grey areas are the 90 % confidence zones for each level of errors, we can observe that the emittance increase gets lower as the the voltage errors are distributed on a larger number of harmonics. For 5 % errors a significant increase just below 40 % is however observed for both planes.

PREDICTED EFFECTS OF THE VOLTAGE ERRORS

In the presented model, we consider that the emittance, ϵ, can be expressed as:

$$\epsilon = \epsilon_0 + \sum_{i=Q,S,T} \sum_n \delta\epsilon_{i,n} \tag{3}$$

where ϵ_0 is the reference emittance without errors and $\delta\epsilon_{i,n}$ is the contribution of the single harmonic errors computed from the study described in the introduction of this paper such as $\delta\epsilon_{i,n} = f(A_{i,n})$. The results presented in this section apply the model of Eq. 3 and the voltage components are the same as the one used in the simulations of the previous section. Figures 7 and 8 present the predicted emittance increases for harmonic content 3 (as presented earlier) and in Figs. 9 and 10 we can see the evolution as a function of the harmonic content. Finally the errors on the predicted values compared to the simulated values are presented on Figs. 11 and 12 (the grey areas represent the standard deviation).

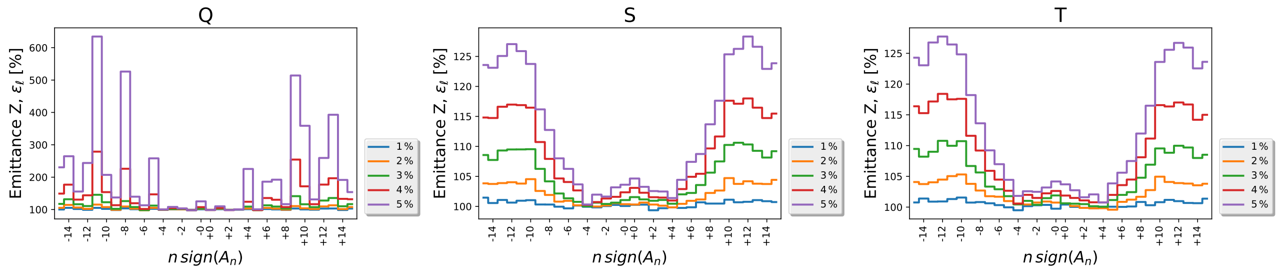

Figure 1: Longitudinal emittance increase due to single harmonic errors.

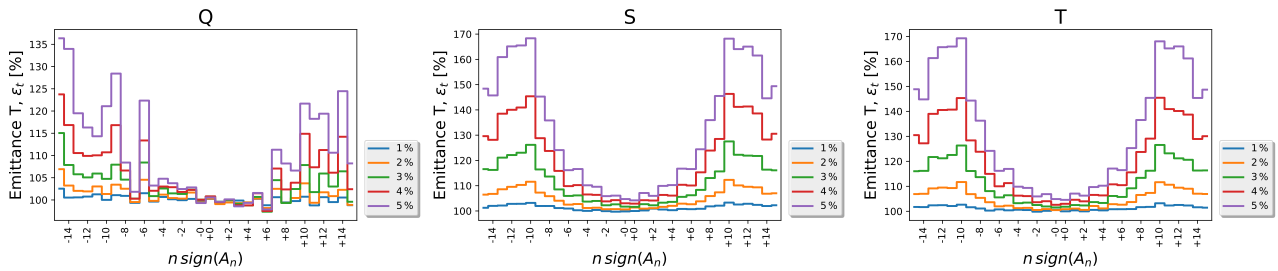

Figure 2: Transverse emittance increase due to single harmonic errors.

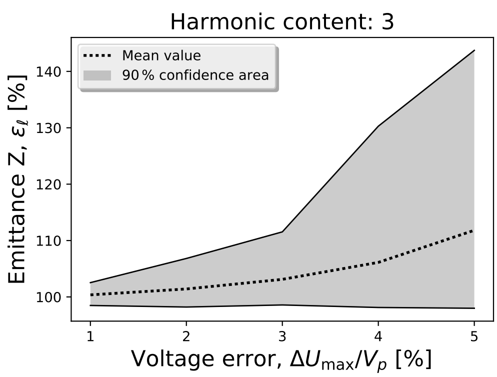

Figure 3: Simulated longitudinal emittance increase as a function of the voltage error.

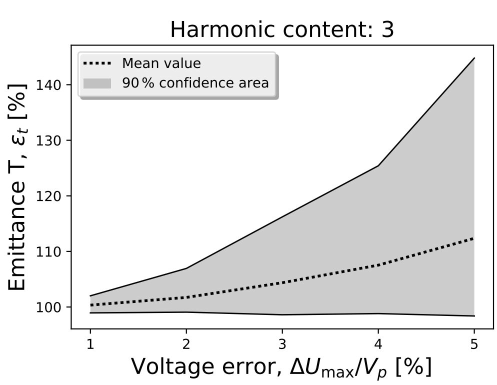

Figure 4: Simulated transverse emittance increase as a function of the voltage error.

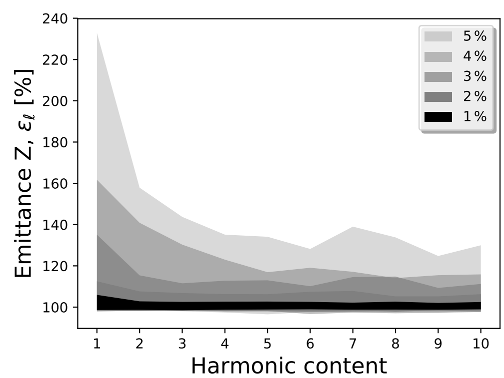

Figure 5: Simulated longitudinal emittance increase as a function of the harmonic content.

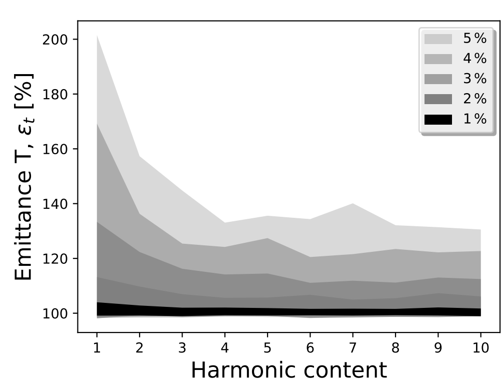

Figure 6: Simulated transverse emittance increase as a function of the harmonic content.

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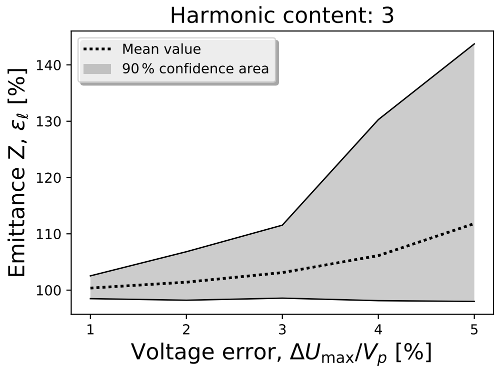

Figure 7: Predicted longitudinal emittance increase as a function of the voltage error.

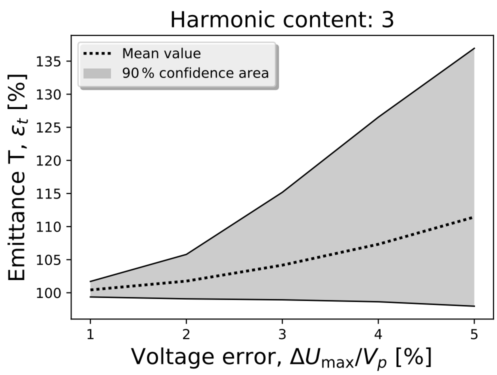

Figure 8: Predicted transverse emittance increase as a function of the voltage error.

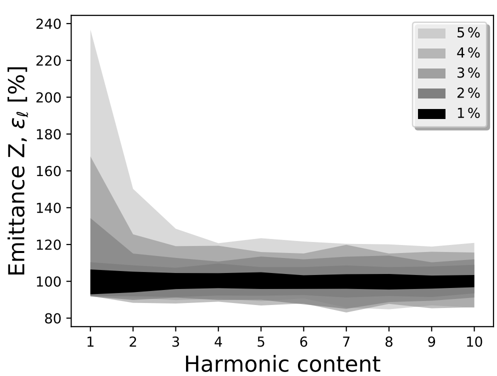

Figure 9: Predicted longitudinal emittance increase as a function of the harmonic content.

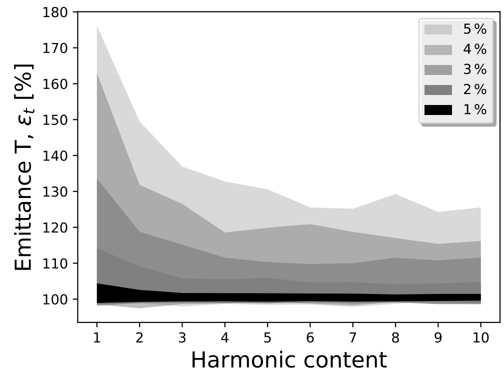

Figure 10: Predicted transverse emittance increase as a function of the harmonic content.

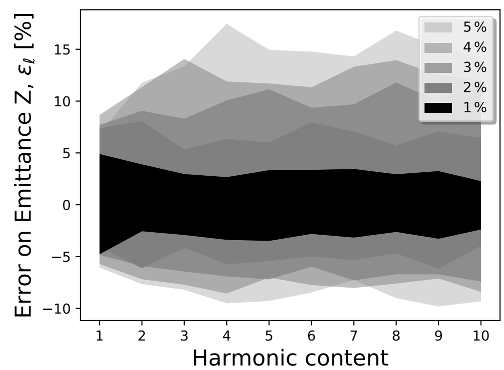

Figure 11: Errors on the predicted longitudinal emittance.

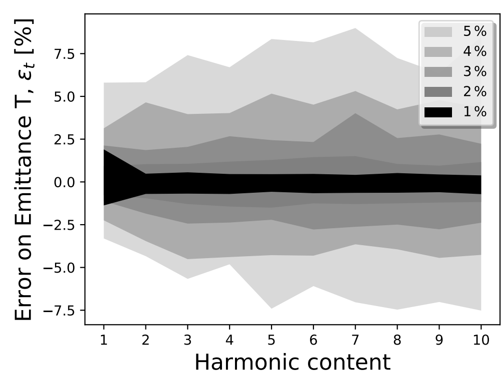

Figure 12: Predicted transverse emittance increase as a function of the harmonic content.

CONCLUSION

While the study shows that the prediction model is valid when one wants to get a statistical view of the voltage errors induced effects on the beam dynamics, we can not conclude that the model can be used to predict the effects of a particular voltage low. The errors on the predicted emittances values are indeed in the same range as the expected emittances increase. A mutiparticle calculation is then mandatory to evaluate the beam quality. On the other hand, the statistical results of the emittances can be evaluated using the simple model saving a lot of simulation time.

In addition to the advice of [1] to stay away from high harmonics during the RFQ tuning phase, the current study suggests to privilege voltage low with a sufficiently large harmonic content to avoid strong effects on the beam quality.

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