VOLTAGE ERROR STUDIES IN THE ESS RFQ

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Abstract

During the fabrication of an RFQ, deviation from the perfect geometry will occur during assembling, brazing and machining the different parts. These geometrical defects will impact the theoretical inter-vane voltage, given by the beam dynamics, by altering the quadrupolar component as well as adding dipolar terms in the voltage function. Tuners can correct partially the effect of the manufacturing. The study summarizes the effects of the voltage errors on the beam quality in the case of the ESS RFQ with a harmonic analysis of the voltage function.

INTRODUCTION

The ESS Radio-Frequency Quadrupole [1,2] (RFQ) is a 4-vanes strucure of $\sim 4.5\,m$ in length composed of 5 segments as can be seen in Fig. 1. The RFQ aims at accelerating the proton beam from 75 keV to 3.62 MeV and transforms the macro-pulse in a train of bunches at 352.21 MHz. It also optimizes the transmission and the beam quality both in the longitudinal and the vertical planes thus allowing (with a suitable choice of the lattice and its parameters [3]) a low loss transport along the linear accelerator (linac).
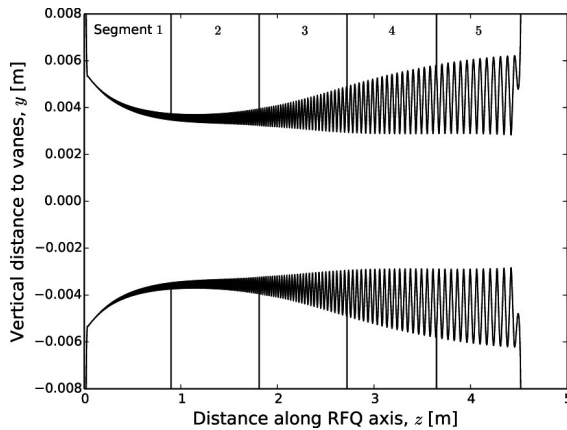

Figure 1: RFQ aperture.

In a perfect RFQ, the inter-vane voltage is given only by the beam dynamics. In reality, nonetheless, slug tuners are always necessary to compensate for construction tolerances. In the ESS case, 15 tuners par quadrant are foreseen to tune the RFQ voltage as close as possible to the theoretical one. In this paper, we present the results of an extensive voltage error study predicting that even small errors on the voltage (a few percent) may impact strongly the beam dynamics. Multi-particle simulations have been performed with the Toutatis code [4] and a $100\,k$ particles, $0.2\,\pi$.mm.mrad rms transverse emittance, 70 mA proton beam transported

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through the Low Energy Beam Transfer line [5] (LEBT) has been considered as an input distribution.
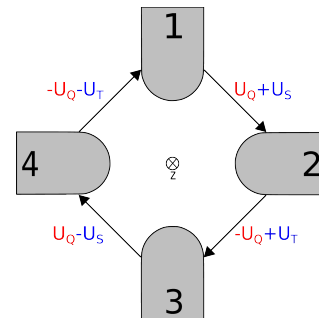
VOLTAGE REPRESENTATION IN THE RFQ

Figure 2: RFQ cross section and vane voltage difference.

In a RFQ of the 4-vanes type, we can show [6] that in the region of the vane tips the voltage difference between vanes can be represented by a set of 3 components as shown in Fig. 2: U_Q is the quadrupolar component, U_S and U_T are both dipolar components. The voltage in the RFQ can then be fully determined by a 3-components vector $U(U_Q, U_S, U_T)$. In the perfect RFQ, the theoretical voltage given by the beam dynamics, V_p, is the only contribution to the RFQ voltage: $U = U_0(V_p, 0, 0)$. In the real RFQ, due to machining errors and imperfect voltage tuning, the voltage vector becomes $U = U_0 + \Delta U$ with $\Delta U(\Delta U_Q, U_S, U_T)$ the voltage error vector. The voltage vector now contains a quadrupolar error, ΔU_Q, and the dipolar components: U_S and U_T. Note that the time varying contribution in $\cos \omega t$ with w the angular frequency of the RF system is omitted in the expression of the voltage in our notation.

SINGLE HARMONIC VOLTAGE ERRORS

We have expressed the components ΔU_i ($i = 1, 2, 3$) of ΔU as a periodic function of z such as:

$$\Delta U_i = A_n \cos \frac{n\pi}{L_{\text{RFQ}}} z \qquad (1)$$

with n the harmonic number being a positive integer, A_n the amplitude (positive or negative) of the error oscillations, L_{RFQ} the RFQ length and z the distance along the RFQ axis. In this section, the beam dynamics have been simulated for all modes up to $n = 15$ for each component of the voltage error vector individually (the others being kept null). The goal was to quantify the "harmfulness" on the beam quality of the harmonics for each of the components in $(\Delta U_Q, U_S, U_T)$. The error range has been limited to $|A_n|/V_p \leq 5\,\%$. For the
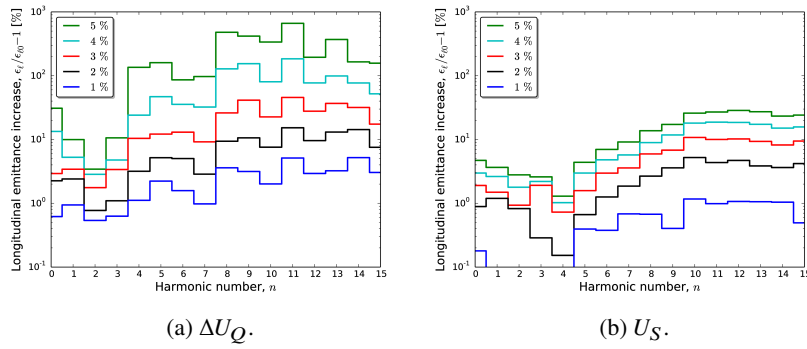
05 Beam Dynamics and Electromagnetic Fields

D01 Beam Optics - Lattices, Correction Schemes, Transport

(a) ΔU_Q.   (b) U_S.

Figure 3: Longitudinal emittance increase.
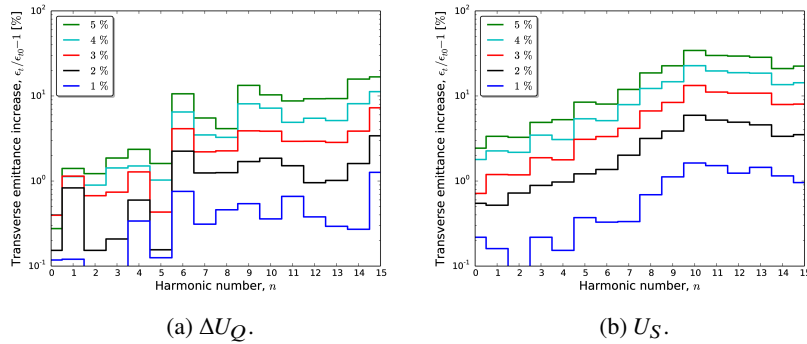

(a) ΔU_Q.   (b) U_S.

Figure 4: Transverse emittance increase.

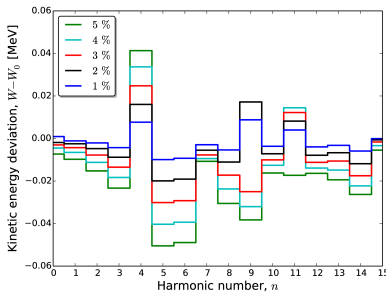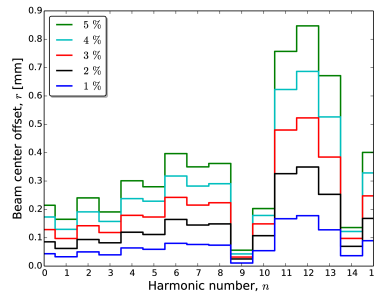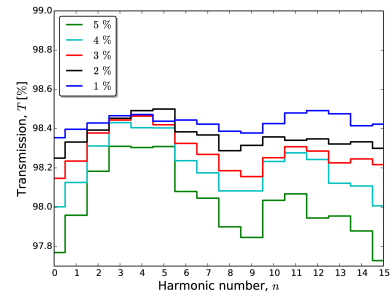Figure 5: Kinetic energy (ΔU_Q).   Figure 6: Beam center offset (U_S).   Figure 7: Transmission (ΔU_Q).

quadrupolar errors, from A_n positive or negative, only the strongest effect is shown. For example, for $n = 1$, a positive tilt (*ie* the voltage component U_Q is higher than V_p at beginning of the RFQ and lower at its end) is more dangerous than a negative tilt thus only the effects of $A_1 > 0$ are presented on the figures. For the dipolar contributions to the voltage, we have limited the visualization of the results to U_S with $A_n > 0$. The 3 other combinations have the same effects on the dynamics despite the fact that deviation of the beam center occurs in a different quadrant.

From Figs. 3 and 4, in which respectively the longitudinal and the transverse emittance increase with respect to the nominal case (denoted by the subscript 0) are shown for ΔU_Q (left) and U_S (right), one can notice the strong influence of the higher harmonics. The increase is greater than 10 % (note the logarithmic scale) for $|\Delta U_Q|/V_p = 2$ % in the

longitudinal plane when $n \geq 8$ for instance. The kinetic energy, plotted in Fig. 5, shows the strongest variation for harmonics 4, 5 and 6 with a difference with respect to the nominal case close to ± 20 keV for errors of 2 %. In Fig. 6, we can see that the highest values of the beam center offset are observed for the harmonics 11, 12 and 13 with more than 0.3 mm offset in the 2 % error case. The transmission, although one can observe some small variations in Fig. 7, remains very high: $T > 97.5$ % in all cases. The results of the study for ΔU_Q on the shift of the beam center and for U_S on the kinetic energy and the transmission are not shown here since they contribute negligibly to those parameters.

COMBINED VOLTAGE ERRORS

While in the previous section we have looked at each mode n independently, we now consider that each component in
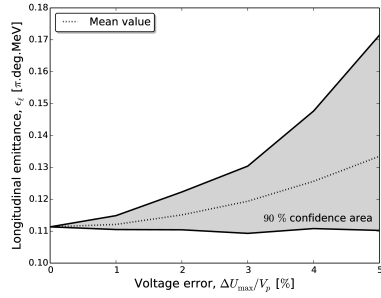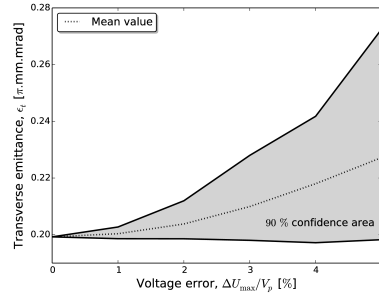
Figure 8: Longitudinal emittance.
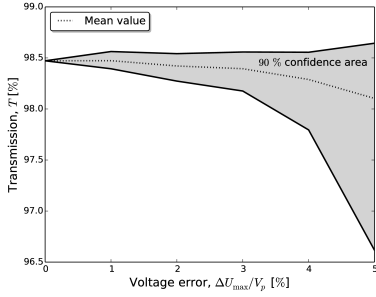

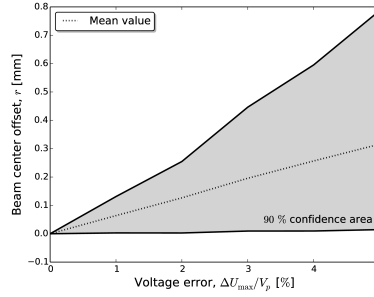Figure 9: Transverse emittance.

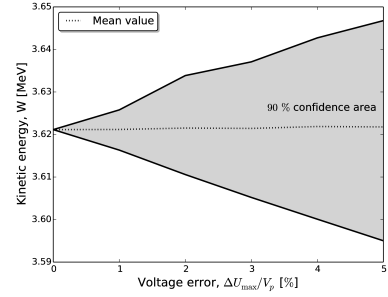Figure 10: Transmission.

Figure 11: Beam center offset.

Figure 12: Kinetic energy.

Table 1: Expected values for $\Delta U_{max}/V_p = 2\,\%$.

Parameter	Symbol	Mean value	90th percentile range	Unit
Longitudinal emittance	ϵ_ℓ	0.1151	$[0.1104; 0.1223]$	π.deg.MeV
Transverse emittance	ϵ_t	0.2038	$[0.1986; 0.2120]$	π.mm.mrad
Transmission	T	0.9842	$[0.9827; 0.9854]$	%
Beam center offset	r	0.1266	$[0.0027; 0.2548]$	mm
Kinetic energy	W	3.6215	$[3.6106; 3.6339]$	MeV

$(\Delta U_Q, U_S, U_T)$ can be written as:

$$\Delta U_i = \sum_{n=0}^{15} A_n \cos \frac{n\pi}{L_{RFQ}} z \qquad (2)$$

where we can see that the upper bound of the sum in Eq. 2 is set to $n = 15$. This choice is motivated by the fact that we assume the action of the slug tuners (15 per RFQ quadrant) to be the main contribution to the spectral content of the RFQ voltage thus the higher order modes can be neglected. In the following study, we have considered that each mode n contributes with the same statistical weight in the sum in Eq. 2 (no mode is considered more probable) with all A_n values randomly generated with a uniform probability distribution. The value of each component of the vector ΔU is then normalized such that ΔU_i is uniformly distributed in $[-\Delta U_{max}; +\Delta U_{max}]$ independently for $i = 1, 2, 3$. We have simulated 1 000 cases for each $\Delta U_{max}/V_p$ in $[1; 2; 3; 4; 5]$ %. Results of the the study are presented in Figs. 8–12 for the longitudinal rms emittance, the transverse rms emittance (norm.), the transmission, the beam center offset and the kinetic energy respectively. For the specific case of $\Delta U_{max}/V_p = 2\,\%$, which is the requirement for the ESS

RFQ voltage tuning, expected values with the 90th percentile range are reported in Tab. 1.

CONCLUSION AND PERSPECTIVES

We have considered that the RFQ voltage components can be expressed as a sum of periodic functions with the higher frequency being determined by the number of slug tuners in one RFQ quadrant. For each mode, the effects of the errors have been evaluated. The study showed that higher modes ($n \geq 7$) are the most dangerous for the beam quality. The effects of the voltage combined errors have also been presented. The study teaches that, in order to preserve the beam quality during operation, not only shall be considered the amplitude of the errors in the RFQ voltage tuning but the spectral content (in z) of the voltage shall also be evaluated. An interesting feature would be to determine the expected beam parameters from the measured modal content of the RFQ voltage during the tuning procedure based on the knowledge of the computed effects the single harmonics for each components in ΔU. This topics will be investigated in a future study.

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