# OPTIMIZATION OF RFQ DESIGN

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*Abstract*

The High Intensity Proton Injector (IPHI) project in France calls for a CW RFQ capable of accelerating 100 mA of proton beam from 95 keV to 5 MeV. Over the years, different parameter-set choices resulting in RFQ designs with varied characteristics have been studied here at Saclay as well as in other laboratories around the world. Methods to achieve optimum parameters where average aperture radius is kept constant is well established. However, optimization of parameters connected to the mechanical geometry and rf are not well established. In this paper, we compare two RFQ designs; one in which the average aperture radius and the vane voltage are kept constant and the other where they are allowed to vary. The relative merits of the two design-choices are discussed.

## 1 INTRODUCTION

In recent years, study of high intensity proton linear accelerators has become an active program at CEA-Saclay. Linacs are widely considered to be the ideal source of spallation neutrons for applications like transmutation of nuclear waste and production of tritium [1]. The IPHI project [2] at Saclay is aimed at demonstration of the front-end of such a high intensity linac. It consists of a CW high intensity light source (SILHI) capable of delivering a 95 keV 100-mA proton beam [3], followed by an RFQ and a DTL bringing the energy up to 5 MeV and 11.5 MeV respectively. Understandably, successful demonstration warrants that each component has high-performance in terms of flexibility and reliability. The RFQ should be able to handle a high power beam with long-term reliability and provide a good quality beam at 5 MeV.

Careful consideration was given to the RFQ design. Different designs as well as methods were looked at and evaluated in terms of beam-dynamics, mechanical aspect and RF. Here, we review two designs; they differ in the way the vane average radius ($R_0$) and the vane voltage (V) are treated. In one, they are kept constant while in the second they are allowed to vary. The first design is complete [4] while the second one is nearly completed. In section 2, we describe the global RFQ parameters, and the essentials of the two designs, while in section 3 we discuss the relative merits of the two design approaches. The results presented here were achieved using two sets of codes. The first is the classical z-code PARMTEQM, while the second one is the t-code LIDOS [5].

## 2 RFQ DESIGN

The frequency, output energy, and current were pre-selected for the RFQ design. The frequency was fixed at 352.2 MHz for the entire linac. The ion-source and LEBT established the parameters for the input beam to the RFQ. The input total normalized beam emittance is 1.5 π.mm.mrad, which corresponds to an rms normalized emittance of 0.25 π.mm.mrad. The goal for transmission through the RFQ was set at 95%, or higher. The high transmission criteria stems from the concern that the effect of appreciable beam loss on the long term performance of the vane tips for such an high power CW RFQ is not yet known. Also, it is generally agreed that an RFQ designed for a high transmission would provide higher transmission in reality compared to one that has poor theoretical transmission to begin with. At the output-end of the RFQ, a transition cell [6] is added to tailor the output beam characteristics.

The peak surface field for the constant $R_0$ design was chosen to be 1.8 $E_k$. ($E_k$ = 18.4 MV/m @ 352 MHz). This is the value chosen for the APT/LEDA RFQ at Los Alamos [7]. This is a compromise between the requirements for beam dynamics and spark-down rate. However, in view of the initial performance of the CRITS RFQ [8], we looked for a design with reduced peak surface field. In the second design we lowered the peak surface field to 1.7 $E_k$. We strived to maintain the transmission above 95%. This was achieved by allowing V and $R_0$ to vary while maintaining $\rho/R_0$ constant to 0.85 - a good compromise in terms of Kilpatrick limit and multipole effects. Four segments, each about 2 m long will be coupled together through resonant couplers [9] to form the ~ 8 m long RFQ. 3D RF simulations also show that about 8 m is the best length for dipolar mode separation for a structure with 3 resonant couplers.

### 2.1 Description of the designs.

The two designs follow the guidelines stated earlier. In both the cases, the longitudinal modulation follows the 2-term potential and have the same transition cell with a fringe field ~2 cm. The beam can be rotated from a divergent beam to a convergent beam if need be by adjusting the fringe field length. Fig.1. shows x-x′ plot of the output beam vs. the fringe field length.

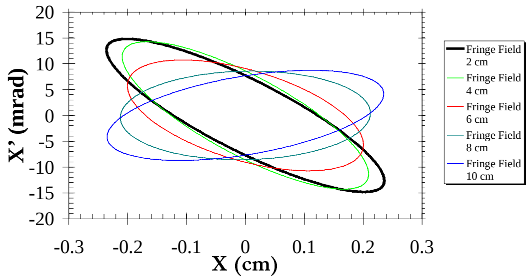


**Figure 1: x-x′ vs. fringe field length**

For the design with both $R_0$ and V constants, we followed a method developed at CEA-Saclay [10]. Table 1 summarizes the parameters.

This design approach leads to a 'bottleneck' in the minimum aperture profile at the end of the gentle buncher, where the minimum aperture has to decrease rapidly in order to accommodate the increasing 'm'.

**Table 1. Parameters of the $R_0$ = Constant Design**

| | |
|---|---|
| Total length | 7.1m |
| Peak surface field | 1.8 $E_k$ |
| Transmission | 97% |
| Total beam-loss power | 1.84kW |
| Copper loss | 1300W/cm |
| Total copper loss (7.1m) | 0.923 MW |
| $R_0$ | 4.04mm |
| Vane voltage | 99.3 kV |
| aperture (a) | 4.04-2.70mm |
| modulation (m) | 1-1.89 |

In the second design, the vane voltage and the mean aperture opening $R_0$ change along the length of the RFQ. The peak surface electric field is also lowered from 1.8 $E_k$ to 1.7 $E_k$. The phase ramp is adjusted as needed. This design has the same length as the previous one but gives a slightly lower transmission, as $E_\kappa$ was decreased.

**Table 2. Parameters of the $R_0 \neq$ Const. Design**

| | |
|---|---|
| Total length | 7.1 m |
| Peak surface Field | 1.7 $E_k$ |
| Transmission | 96% |
| Total beam-loss power | 2.2 kW |
| Copper loss | 1296 - 2222W/cm |
| Total copper loss (7.1m) | 1.05 MW |
| $R_0$ | 4.58-6.06 mm |
| Vane voltage | 101.5-140.56 kV |
| aperture (a) | 4.03 - 4.58 mm |
| modulation (m) | 1-1.893 |

The 'bottle-neck' in 'a' is almost eliminated. Each part of the RFQ is optimized by closely inspecting the behavior of the dynamic parameters. Mainly, we kept the transverse focusing strength as high as possible until past the gentle buncher section, while in the longitudinal plane the aperture was kept as large as possible. Table 2 summarizes the design parameters.

## 2.2 *Design comparisons.*

The two designs produced same output beam in terms of dynamical parameters. The output transverse rms normalized emittance in both the cases was 0.26 π.mm.mrad. Figures 2 (a) and (b) show the main parameters as a function of the cell number for both the designs.

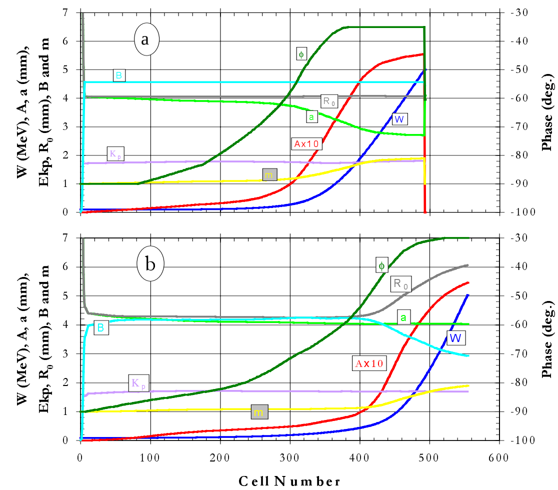


**Figure 2: RFQ parameters vs. cell length for (a) $R_0$ = Constant and (b) $R_0 \neq$ Constant designs.**

The total deposited power due to beam loss is almost the same in both the cases. The small difference is probably due to 1% difference in transmission.

In order to make a comparison, we made some errors studies for both the cases. For example, sensitivity to beam misalignment is an important criteria for an RFQ. Figure 3 shows transmission for the two cases as a function of input beam misalignment. The $R_0$ = Const design shows a relatively greater sensitivity to beam misalignment.

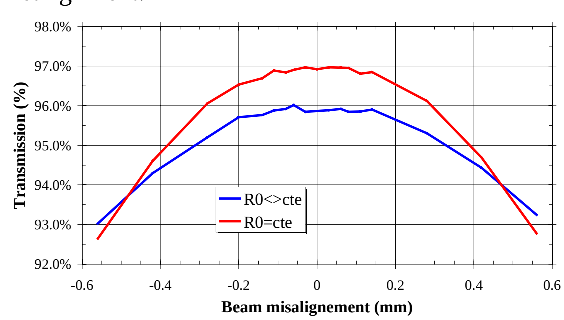


**Figure 3: Transmission vs. input beam misalignment for the two designs.**

Figure 4 shows that for the same misalignment, the output beam emittance is the same for both the designs. All of the above observations could be explained in terms of a 'bottleneck' in the $R_0$ = Const design.

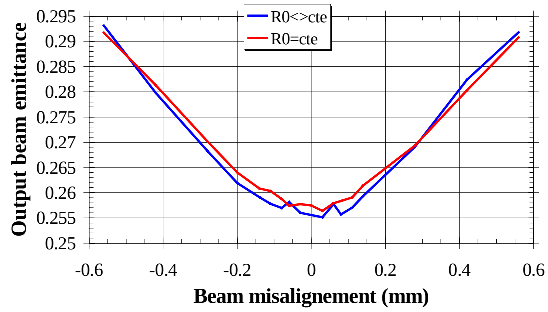


**Figure 4: Output beam emittance for the two designs**

The sharp reduction in 'a' makes it more sensitive to misalignment. On the other hand, in the $R_0 \neq$ constant design, beam losses occur all along the cavity, making it less sensitive to input misalignment. This is corroborated by the emittance results shown in Fig.5. Transmission falls off more rapidly with increasing emittance (larger beam in real space) for $R_0$ = Constant design.

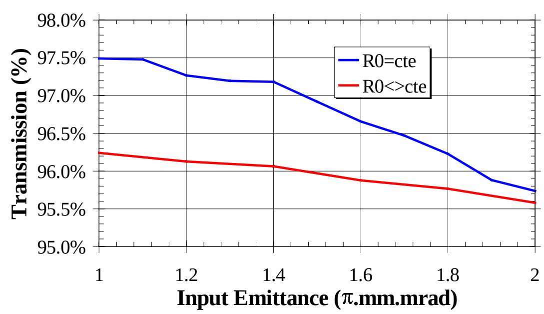


**Figure 5: Emittance dependence of transmission for the two designs.**

Figure 6 shows the effect of reduced focusing on the current limit. In the $R_0 \neq$ constant design, the peak surface field is reduced at the cost of focusing strength. One of the consequences is that the current limit is not the same for the two designs. The saturation accelerated beam-current in the $R_0 \neq$ constant design is lower and is reached for a lower input beam current.

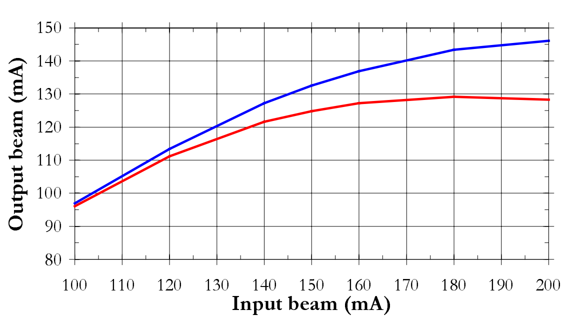


**Figure 6: Saturation current for the two designs.**

## 3. RELATIVE MERITS

Both designs have relative merits and demerits. The $R_0$ = constant design allows to keep the transverse vane-tip profile same throughout the length of the RFQ. Vane tip machining becomes relatively straightforward in such a geometry. This also makes RF tuning of the cavity much simpler. The cavity resonance volume does not change along the RFQ. This makes the mechanical design of the cavity simpler. An important advantage with $R_0$ = constant design is realized in the design phase. An optimum design involves finding a solution in a multi-parameter space. It turns out that keeping $R_0$ constant makes the optimization process relatively straightforward. In fact, we do have well charted method [10] that allows one to design an RFQ with a transmission better than 95% in less than a couple of days time. On the other hand, when $R_0$ is varied, the design procedure is not well charted; it is more intuitive and longer iterative steps are needed to arrive at an optimized solution.

The disadvantage of the $R_0$ = constant method is that it does not offer any flexibility in terms of focusing in the RFQ. Variation of $R_0$ provides a direct key to tailor the focusing strength; one can open up the bore where it is needed and not exceed the peak surface field. This additional flexibility makes such design more attractive. It becomes feasible to have nearly the same transmission with reduced peak surface electric field.

The other important consideration is the question of loss. Keeping mean aperture constant invariably leads to a 'bottleneck' in the aperture leading to localized beam loss in the RFQ. By varying $R_0$ one can distribute the loss along the length of the RFQ.

## 4. CONCLUSION

Two representative designs of RFQ described above, one with mean aperture radius constant and the other varying, show that it is possible to obtain nearly the same performance in both the cases. However, the variable mean aperture radius design permits to have a lower peak surface field. This also shows less sensitivity towards input beam misalignment and emittance variation.

## 5. REFERENCES

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