

CHOICE OF PARAMETERS FOR THE CERN HIGH INTENSITY RFQ (RFQ2 PROJECT)

C. Biscari and M. Weiss

European Organization for Nuclear Research  
CERN, Geneva, Switzerland

Summary

After the successful completion and operation of the CERN 520 keV, 80 mA RFQ (RFQ1 project), feasibility studies for a new 750 keV, 200 mA RFQ (RFQ2 project) have been undertaken. With the experience gained in the past years and with a careful choice of operating parameters, a RFQ with the above specifications seems to be perfectly achievable.

RFQ2 is intended to inject protons into Linac 2.

Introduction

The RFQ programme at CERN was started in 1981 with the idea of replacing progressively the preinjectors of Linac 1 and 2 (520 and 750 keV respectively) with simpler devices, which have been tried out at LANL in 1980<sup>1</sup>. The first part of this programme has been successfully completed and RFQ1 is now operational on Linac 1<sup>2</sup>; the second part, RFQ2, which is a much more ambitious undertaking, benefits from the practical experience gained over the past years as well as from advancements of the state of the art.

RFQ2 will feed the Linac 2 and is supposed to deliver ~200 mA of protons, at 750 keV. The frequency is 202.56 MHz, the pulse length 150 μs and the repetition rate is 2 pulses per second.

This paper shows a feasibility study of such an accelerator; in fact, with electric fields of < 35MV/m (according to experience with RFQ1 they can be held) a RFQ2 with the above specifications is possible.

Analytic Approach

Only the essential steps will be considered; the knowledge of basic RFQ formulae is assumed. The notation is as introduced by LANL.

A logical approach to the design of a high intensity RFQ is by analysing the zero current betatron and synchrotron phase advances  $\sigma_{OT}$  and  $\sigma_{OL}$  and the corresponding space charge factors  $\mu_T$  and  $\mu_L$  in the critical cells of the accelerator. These cells are at the end of the gentle buncher, where space charge forces have their maximum value. There are defined the transverse and longitudinal current limits<sup>3,4</sup>:

$$I_T = \frac{4mc^2}{3Z_0e} \frac{\beta |\phi_S|}{\lambda} \frac{E_N}{1-f(\bar{T}/b)} \frac{\mu_T}{\sqrt{1-\mu_T}} \sigma_{OT} \quad (1a)$$

$$I_L = \frac{2mc^2}{3Z_0e} \frac{\beta |\phi_S|}{\lambda} \frac{E_N}{f(\bar{T}/b)} \frac{\mu_L}{\sqrt{1-\mu_T}} \frac{\sigma_{OL}^2}{\sigma_{OT}} \quad (1b)$$

with  $Z_0 = 1/\epsilon_0 c$  and  $E_N$  and  $f(\bar{T}/b)$  being the normalized beam emittance and the beam form factor, respectively. Note that formulae (1) are obtained by linearizing all the forces, which is not really justified for (1b); the results are therefore used only as indications. For  $I_L = I_T$  it follows:

$$\mu_L = \frac{2f(\bar{T}/b)}{1-f(\bar{T}/b)} \frac{\sigma_{OT}^2}{\sigma_{OL}^2} \mu_T \quad (2)$$

The space charge factors have, of course, to be smaller than 1, even, if possible, smaller than 0.84<sup>5</sup>.

The values of  $\sigma_{OT}$  and  $\sigma_{OL}$  can neither be chosen freely, as they determine the voltage between the vanes (in fact vane tips). For the voltage, it suffices to start with the lowest order potential function, containing only two terms:

$$V = \chi V + AVI_0(ka) \quad (3)$$

where

$$\chi V = 2\sqrt{2}\pi \frac{mc^2}{e\lambda^2} a^2 \sqrt{\sigma_{OT}^2 + 0.5\sigma_{OL}^2} \quad (4)$$

$$AV = \frac{mc^2}{\pi^2 e} \frac{\beta^2}{|\sin\phi_S|} \sigma_{OL}^2 \quad (5)$$

By fixing the energy and synchronous phase at the end of the gentle buncher and specifying  $\sigma_{OT}$  and  $\sigma_{OL}$ , one has determined

$$\frac{\chi V}{a^2} \quad \text{and} \quad AV$$

which can be written as  $C_1$  and  $C_2$ , respectively. Formula (3) is now :

$$V = C_1 a^2 + C_2 I_0(ka) \quad (6)$$

where  $a$  is the minimum aperture radius determined by the average beam radius (matched), the wobble factor  $\psi$  and the space charge factor  $\mu_T$ :

$$a = \frac{r\sqrt{\psi}}{(1-\mu_T)^{1/4}} = \left[ \frac{\lambda E_N}{q_T \sqrt{(1-\mu_T)}} \frac{\pi\sqrt{2} + (\sigma_{OT}^2 + 0.5\sigma_{OL}^2)^{1/2}}{\pi\sqrt{2} - (\sigma_{OT}^2 + 0.5\sigma_{OL}^2)^{1/2}} \right]^{1/2} \quad (7)$$

The second term in formula (6) is greater than the first; hence, if one wishes to keep  $V$  low,  $\sigma_{OL}$  is the predominant factor. This remains true, although to a lesser extent, even if one increases somewhat the aperture for safety margins.

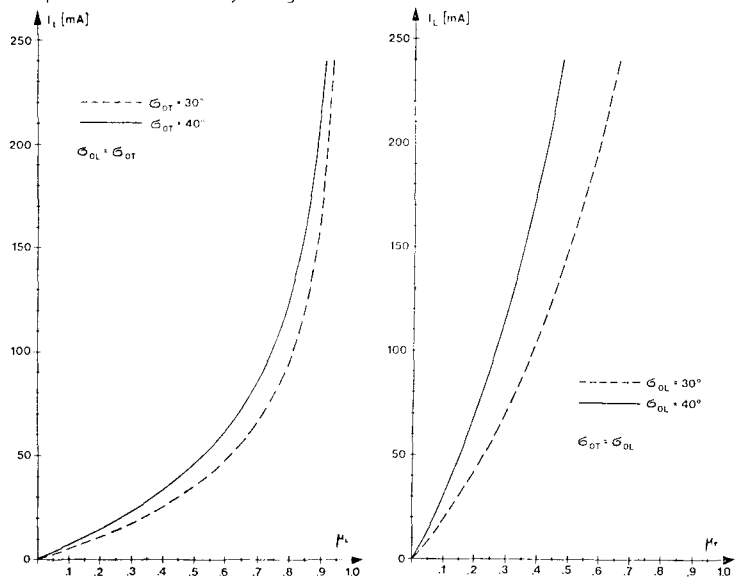
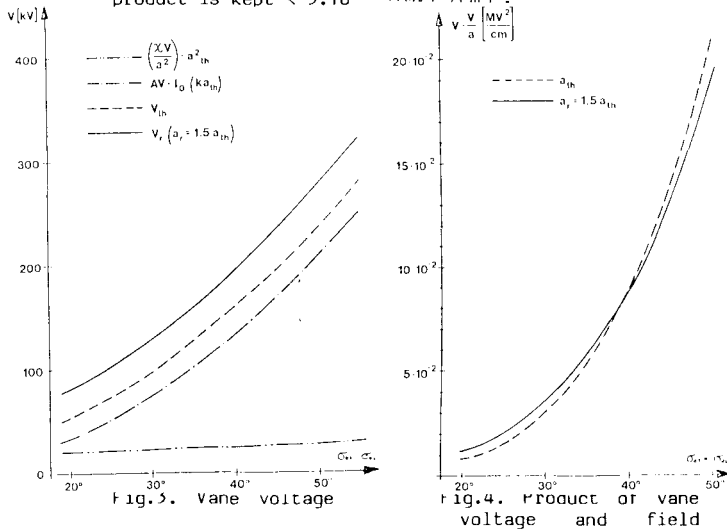


Fig. 1 and 2. Transverse (1) and longitudinal (2) current limits

The Figs. 1 and 2 represent  $I_T$  and  $I_L$  as functions of  $\mu_T$  and  $\mu_L$ , respectively. To simplify the graphs,  $\sigma_{0T}$  and  $\sigma_{0L}$  are taken equal and  $\mu_T$  and  $\mu_L$  satisfy formula (2). Complementary to Figs. 1 and 2 is the Fig. 3, where the terms of the formula (3) and the vane voltage are shown. Fig. 4 shows an important product between the vane voltage and the maximum vane tip field ( $\sim$  related to the peak surface field). To avoid breakdown problems, this product is kept  $< 5 \cdot 10^{-2} \text{ (MV)}^2 / (\text{cm})^2$ .



The above figures give useful indications for the choice of RFQ parameters :

- a) the values of  $\sigma_{0T}$  should be somewhat greater than  $\sigma_{0L}$  (Figs. 1, 2).
- b)  $\sigma_{0T}$  and  $\sigma_{0L}$  cannot be too big if the voltage and peak field have to remain in reasonable limits (Figs. 3, 4).
- c) The value of  $\mu_T$  becomes of the order of 0.9 for  $\sigma_{0T} \approx 35^\circ$  (Fig. 1).
- d) The aperture also influences the vane voltage (Fig. 3).

As mentioned, the above procedure gives a guideline and the limits for the choice of RFQ parameters; they are then actually determined by computer programs.

Computer optimization

The computational approach to the RFQ design is essentially the same as developed at LANL. The procedure of choosing and optimizing the parameters, however, follows the steps outlined in the previous chapter.

The first program in the series, INPAR, determines the main RFQ parameters (at the end of the gentle buncher) from input data containing, amongst others,  $\sigma_{0T}$ ,  $\sigma_{0L}$ ,  $I$  and  $E_N$ . The procedure is repeated if criteria concerning the vane voltage  $V$  and the product  $V \cdot V/a$  are not satisfied. The resultant space charge factors  $\mu_T$  and  $\mu_L$  are high, 0.9 and 0.65 respectively (increasing  $\mu_L$  above 0.7 drops the RFQ efficiency considerably. This is understandable if one considers the highly asymmetric potential well for synchrotron motion and the inaccuracy coming from the linearization of the forces).

Another important factor of the RFQ is its length,  $L_T$ , which is influenced by the length of the shaper,  $L_{Sh}$ , and input energy,  $W_{in}$ . The input energy is chosen  $> 50 \text{ keV}$  for space charge reason (see

later), but stays  $\leq 100 \text{ keV}$  for HT simplicity. Figs. 5 and 6 show  $L_T$  and  $L_{Sh}$  as functions of the energy at the end of shaper,  $W_{Sh}$ ; the acceleration section is omitted for better clarity of the analysis. In both Figs. one sees interesting regions concerning the vane voltage  $V$  and the product  $V \cdot V/a$  (hashed), where a good compromise between length  $L_T$  and efficiency exists. For the same vane voltage, the RFQ is shorter when the  $W_{in}$  is higher.

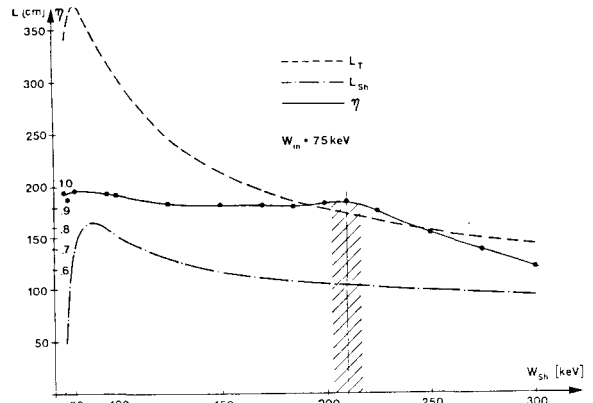


Fig. 5. RFQ length and efficiency ( $W_{in} = 75 \text{ keV}$ )

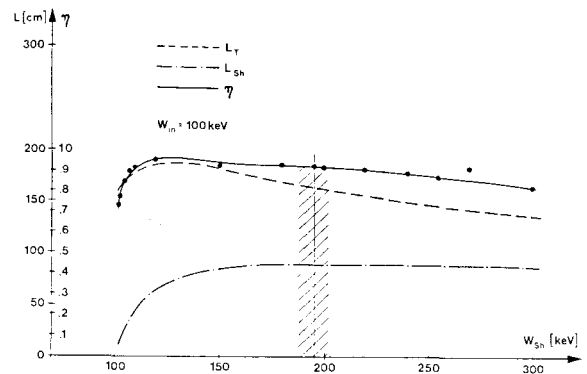


Fig. 6. RFQ length and efficiency ( $W_{in} = 100 \text{ keV}$ )

The introduction of an acceleration section, kept out so far, has also the effect of shortening the RFQ but the efficiency is reduced. In Fig. 7 the results of such an analysis are presented as functions of the energy at the end of the gentle buncher,  $W_{GB}$ .

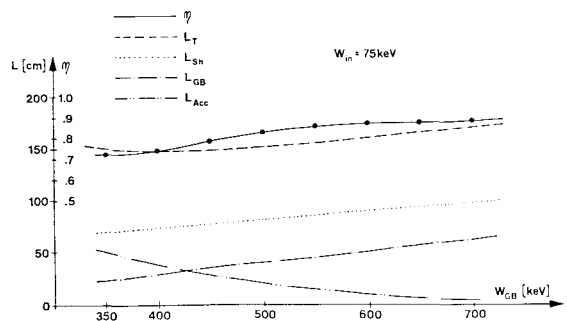


Fig. 7. RFQ with acceleration section

Finally, it remains to determine  $W_{in}$  by considering beam matching problems at the low energy end. To match the beam into the RFQ, two pulsed solenoids are used (as was done in the RFQ1 project). Figs 8 and 9 show the evolution of the matched beam envelopes between the accelerating column and the RFQ. The higher  $W_{in}$  (Fig. 9) is preferable for the solenoids: the required flux of the magnetic field is smaller, which is important to avoid serious iron saturation problems.

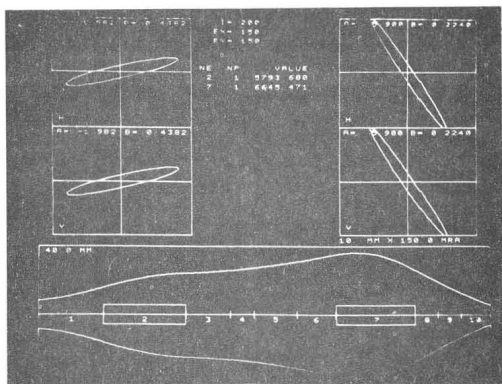


Fig. 8. Beam in LEBT ( $W_{in} = 50$  keV)

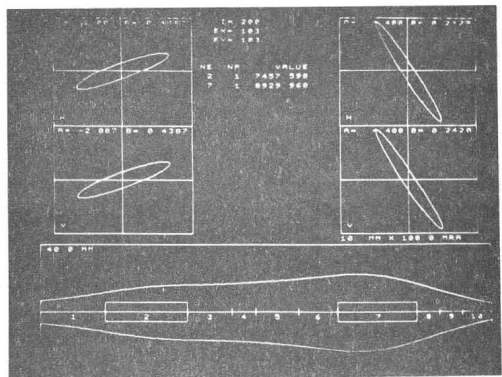


Fig. 9. Beam in LEBT ( $W_{in} = 100$  KeV)

It should also be noted that a radial matching section of the length of  $3 \beta \lambda$  has been found adequate for the RFQ.

Tentative parameters for RFQ2

According to the previous chapters, the RFQ2 parameters are already approximately known. It remains now to fix them more precisely. The normalized emittance of a 200 mA beam ("equivalent" beam, i.e. of uniform density in real space) has been estimated as

$$1 \pi \text{ mm mrad} < E_N < 2 \pi \text{ mm mrad}$$

In all the computations, so far, one has put  $E_N = 1.5 \pi \text{ mm mrad}$ . The efficiency of the RFQ had, hence, to be checked for other emittances, e.g.  $1 \pi$  and  $2 \pi$ : the efficiency remained practically the same.

In analysing various alternatives for the RFQ, one has always checked the peak surface field  $E_S$  (occurring usually in the shaper). In fact, this is

the factor which, in the last run, makes a RFQ feasible or not. RFQ1 has a nominal  $E_S \approx 25$  MV/m, but the whole available RF power (twice the nominal) could have been fed in without problems. This makes us believe that  $E_S \approx 35$  MV/m could be held<sup>8</sup>. Such fields have been computed for RFQ2, see Fig. 10.

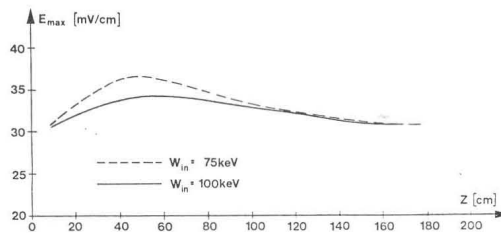


Fig. 10. Peak surface field

The tentative parameters for RFQ2 are listed below:

RFQ 2		Beam	
Frequency (MHz)	202.56	Input current (mA)	~25
Input energy (keV)	100	Input norm. emitt.	$1.5\pi$
Output energy (keV)	750	$4 \times E_{Nrms}$ (mmmrad)	200
Repet. rate ( $s^{-1}$ )	2	Output current (mA)	200
Beam pulse length ( $\mu s$ )	150	Output norm. emitt.	2.2
Vane voltage (kV)	178	$5 \times E_{Nrms}$ (mmmrad)	20
Output sync. phase ( $^\circ$ )	-35	Energy spread (keV)	28.5
Mean app. rad. (cm)	.81	Phase spread ( $^\circ$ )	.58
Minimum app. rad (cm)	.58		

Conclusions

The purpose of this study was to find out if a 200 mA, 750 keV RFQ is feasible or not. The parameters of the RFQ2 are preliminary. Most of the computations have been made with a transverse radius of curvature of the vanes  $\rho_T = r_0 = \text{const}$ . The matching RFQ2 - Linac 2 is under study; the resonator and related problems will be studied.

Acknowledgements

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