ELECTRON-RFQ: A POSSIBLE NOVEL ELECTRON HIGH BRIGHTNESS CURRENT INJECTOR

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Abstract

The increasing interest for high brightness electron injectors, expecially for FEL applications, stimulated the study on the feasibility of a RFQ for electrons (ERFQ).
In this paper this study is described.

Introduction

The Radio-Frequency-Quadrupole gun, invented by Kaptchinskii and Tepliakiov [1], and up to now used only for heavy ions, in principle can accept, focus and accelerate to the decided energy any kind of charged particles. In general, the main advantages of RFQ are small size, low voltage d.c. injection, bunching with high efficiency, high beam current capacity, high output beam quality.

In this paper an ERFQ design is proposed that keeps these advantages even in a non-classical situation and that results in a possible injector in particular for FEL application of the race-track microtron in construction at Frascati [2].

ERFQ characteristics

Injection energy	5 keV
Injection current	150 mA
Output energy	150 keV
Output peak (μbunch) current	>1 A
μbunch lenght (FWHM)	1 cm
Capture efficiency	>90 %
Energy spread (FWHM)	10 keV
Emittance (normalized)	<20 mm mrad
RF frequency	2.998 GHz
Intervane voltage	40 KV
Inner radius	8 mm
Outer radius	23 mm
Total lenght	62 cm
RF peak power	80 KW
Z shunt	20 KΩ/m
B (focusing parameter)	11.94

ERFQ fields

In the GHz frequency region the external radius of the ERFQ cavity is no longer much bigger than the internal radius in which accelerating and focusing fields exist and so it is necessary to leave the usual electrostatic fields treatment [1] and to use correct electromagnetic fields.

Electromagnetic field distribution was obtained in a previous paper [3]:

Modulation free region:

$$E_z=0$$

$$E_r=2\cdot c\cdot B_o\cdot\frac{J_2(K_o\cdot r)}{K_o\cdot r}\cdot\cos(2\cdot\Theta)\cdot\sin(w\cdot t) \qquad K_o=\frac{w}{c}$$

$$E_\Theta=-c\cdot B_o\cdot J'_2(K_o\cdot r)\cdot\sin(2\cdot\Theta)\cdot\sin(w\cdot t)$$

$$B_z=B_o\cdot J_2(K_o\cdot r)\cdot\sin(2\cdot\Theta)\cdot\cos(w\cdot t)$$

$$B_r=0$$

$$B_\Theta=0$$

Modulated region:

$$E_z=E_o\cdot I_o(K'\cdot r)\cdot\sin(K\cdot z)\cdot\sin(w\cdot t)$$

$$E_r=[2\cdot c\cdot B_o\cdot\frac{J_2(K_o\cdot r)}{K_o\cdot r}\cdot\cos(2\cdot\Theta)+ -\frac{K}{K'}\cdot E_o\cdot I_1(K'\cdot r)\cdot\cos(K\cdot z)]\cdot\sin(w\cdot t)$$

$$E_\Theta=-c\cdot B_o\cdot J'_2(K_o\cdot r)\cdot\sin(2\cdot\Theta)\cdot\sin(w\cdot t)$$

$$B_z=B_o\cdot J_2(K_o\cdot r)\cdot\sin(2\cdot\Theta)\cdot\cos(w\cdot t)$$

$$B_r=0$$

$$B_\Theta=\frac{K\cdot E_o}{K'\cdot c}\cdot I_1(K'\cdot r)\cdot\sin(K\cdot z)\cdot\cos(w\cdot t)$$

$K'^2=K^2-K_o^2$, $K=2\pi/L$, L=cell lenght.

$$E_o=\frac{V_o\cdot K'^2[J_1(m\cdot K_o\cdot a)-m\cdot J_1(K_o\cdot a)]}{k\cdot d}$$

$$B_o=\frac{V_o\cdot K_o^2\cdot m\cdot a\cdot[I_o(K'\cdot a)+I_o(m\cdot K'\cdot a)]}{2\cdot c\cdot d}$$

$$d=m\cdot I_o(m\cdot K'\cdot a)[2\cdot J_1(K_o\cdot a)-K_o\cdot a]+ +I_o(K'\cdot a)[2\cdot J_1(m\cdot K_o\cdot a)-m\cdot K_o\cdot a]$$

with: m = vane modulation depht
a = lower radius.

Radial matching section:

$$E_z=\sum_{n=1}^{M} E_n\cdot I_2(K_n\cdot r)\cdot\cos(a_n\cdot z)\cdot\cos(2\Theta)\cdot\sin(w\cdot t)$$

$$E_r=\sum_{n=1}^{M}[a_n\cdot\frac{E_n}{K_n}\cdot I'_2(K_n\cdot r)-2\cdot c\cdot\frac{K_o\cdot B_n}{K_n^2\cdot r}\cdot I_2(K_n\cdot r)]\cdot \cdot\sin(a_n\cdot z)\cdot\cos(2\Theta)\cdot\sin(w\cdot t)$$

$$E_\Theta=\sum_{n=1}^{M}[-2\cdot\frac{a_n\cdot E_n}{K_n^2\cdot r}\cdot I_2(K_n\cdot r)+c\cdot\frac{K_o}{K_n^2}\cdot B_n\cdot I'_2(K_n\cdot r)]\cdot \cdot\sin(a_n\cdot z)\cdot\sin(2\Theta)\cdot\sin(w\cdot t)$$

$$B_z=\sum_{n=1}^{M} B_n\cdot I_2(K_n\cdot r)\cdot\sin(a_n\cdot z)\cdot\sin(2\Theta)\cdot\cos(w\cdot t)$$

$$B_r=\sum_{n=1}^{M}[\frac{2\cdot K_o\cdot E_n}{c\cdot K_n^2\cdot r}\cdot I_2(K_n\cdot r)-a_n\cdot\frac{B_n}{K_n}\cdot I'_2(K_n\cdot r)]\cdot \cdot\cos(a_n\cdot z)\cdot\sin(2\Theta)\cdot\cos(w\cdot t)$$

$$B_\Theta=\sum_{n=1}^{M}[\frac{K_o\cdot E_n}{c\cdot K_n}\cdot I'_2(K_n\cdot r)-\frac{a_n\cdot B_n}{K_n^2\cdot r}\cdot I_2(K_n\cdot r)]\cdot \cdot\cos(a_n\cdot z)\cdot\cos(2\Theta)\cdot\cos(w\cdot t)$$

$K_n^2=a_n^2-K_o^2$,
a_n's odd multiples of $\pi/2H$,
H=RMS lenght.

$$B_n=\frac{B_o\cdot K_o^2}{\sin(a_n^2\cdot H)\cdot K_n^2}\cdot\prod_{\substack{i=1\\ i\neq n}}^{M}\frac{a_i^2}{a_i^2-a_n^2}, \qquad E_n=\frac{c\cdot a_n\cdot B_n}{K_o}$$

These fields match up to M-th order in r the modulation free region fields.

ERFQ design

When the initial and final energies and frequency are specified the RFQ design is determined when three indipendent functions $a(z)$, $m(z)$, $\phi(z)$ are given. The variation of those parameters is determined by the undergoing of the beam to the transformation from continous to bunched, so the action of the RFQ must be adapted to the requirements of the particle dynamics along the structure. Following the Los Alamos design [4], a RFQ is usually divided in four sections:

- -Radial Matching Section(RMS)
- -Shaper
- -Gentle Buncher
- -Accelerating Section

-The RMS provides the transition from a beam having time-indipendent characteristics to one that has the proper variations with time while the focusing strenght increases to the final value. The lenght of the section is adjusted for the overlap between the injected beam phase space area and the RFQ acceptance.

-In the Shaper the accelerating field is increased ,while ϕ_S begin at about -90° and is mantained to a large value in order to obtain a high capture efficiency.

-In the Gentle buncher the bunching action that begun in the Shaper is completed and the values of m ϕ_S and a reach their final values.

-In the Accelerating Section ϕ_S,m and a are held constant and the beam energy grows to the final value.

ERFQ dimensions

RADIAL MATCHING SECTION:

Lenght=4.16 cm
The focusing parameter B grows from 0 to 11.94 according to the RMS fields.

SHAPER:

Lenght=16.12 cm
The bucket lenght decreases up-rigth from 1.38 cm to 1.10 cm.
Number of cells=23
The sincronous phase decreases from 90° to 79.4°.
The modulation parameter m grows according to:
(a) m=1+.003*n+17.E-6*n**3
(n is the cell number)
Minimum radius=7.3 mm
Output energy=5.73 Kev

GENTLE BUNCHER:

Lenght=22.16 cm
The bucket lenght is fixed to 1.10 cm
Number of cells=17
The sincronous phase decreases from 79.4° to the final value 25.99°.
m grows up to the final value 2.3034 according to (a).
Minimum radius=4.71 mm
Output energy=79.6 KeV

ACCELERATING SECTION:

Lenght=17.15 cm
The sincronous phase and m are fixed.
Number of cells=6
Minimum radius=4.85 mm
Output energy=141.13 KeV

Computer simulation

We made also some preliminary computer simulations in order to estimate beam propagation in the ERFQ including the effect of the space charge: in these calculations the electrons are treated as rings that interacts radially and longitudinally between them.

The results of these approximate calculations for a gun current of 150 mA are summarized in the figures 1,2,3,4,5.

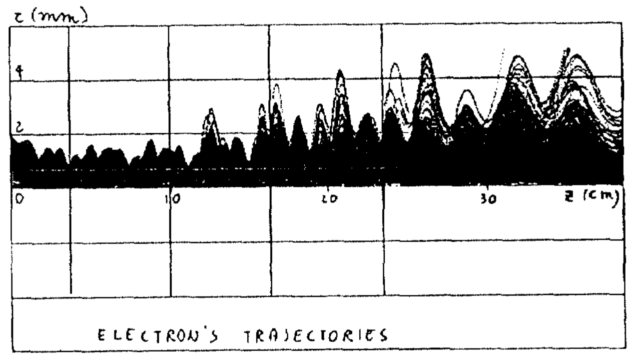
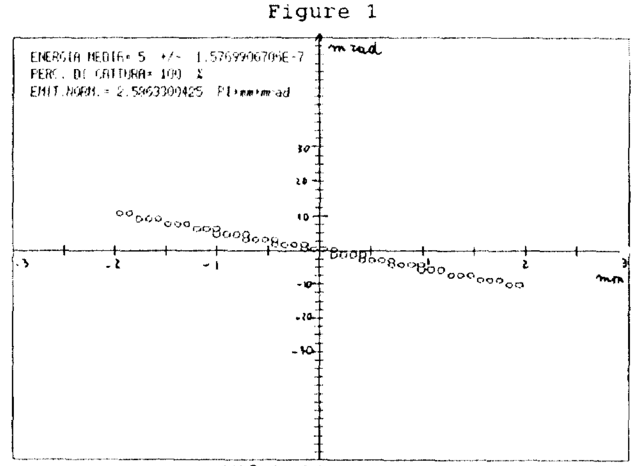
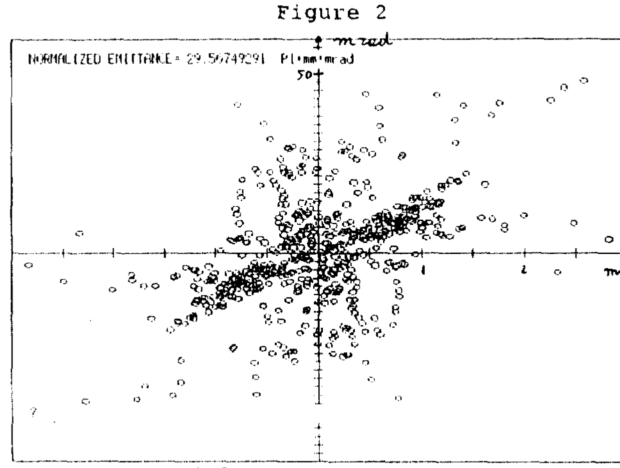


Figure 1



INPUT EMITTANCE

Figure 2



OUTPUT EMITTANCE

Figure 3

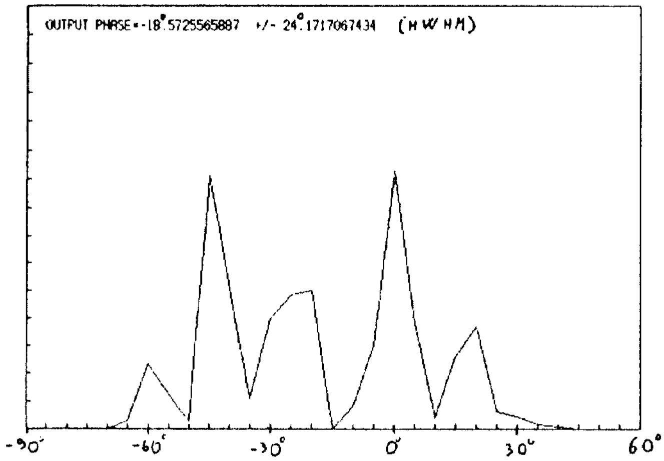


Figure 4

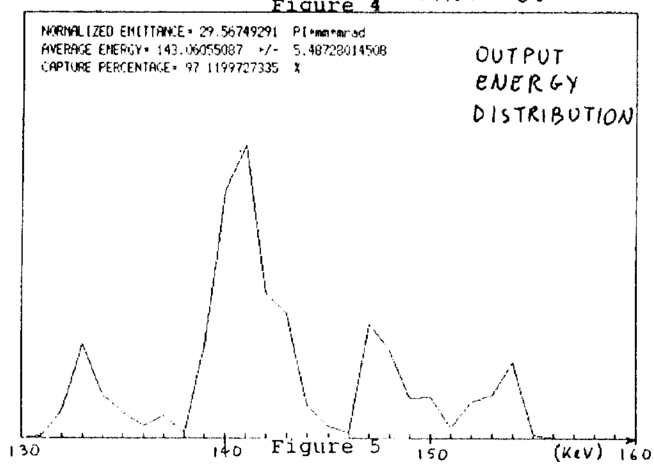


Figure 5

RF measurements

The ERFQ cavity has been studied both computationally and on RF bench. By OSCAR2D code [5] the following parameters have been found for an ERFQ cavity :

Frequency of q-pole mode .... 3.236 GHz
Shunt impedance .... 20 KΩ
Frequency of dipole mode .... 2.884 GHz

In order to check these results a 20 cm long modulation free structure has been constructed [fig. 6] and the following parameters have been measured:

Frequency of q-pole mode .... 3.260 GHz
Frequency of dipole mode .... 2.904 GHz

In this structure many dipole and q-pole superior modes can be clearly seen and easily recognized by means of different excitation/detection posts in longitudinal and in transverse positions. We obtained the mode distribution shown in fig.7.

It is easily seen that differently from ions structures at low frequencies, in this case the separation of dipole and quadrupole modes is quite good and therefore there is no need of mode suppressing items.

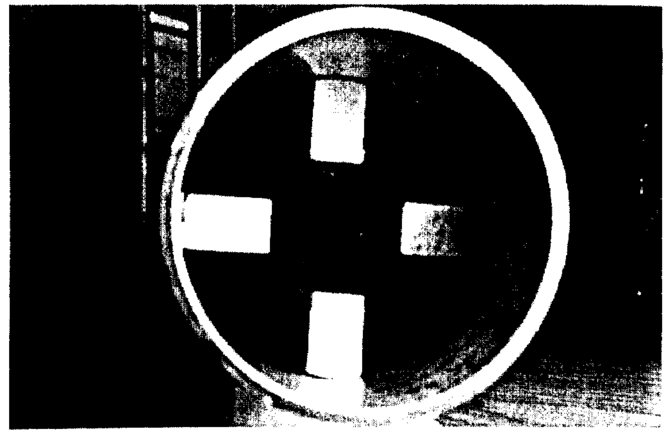


Figure 6

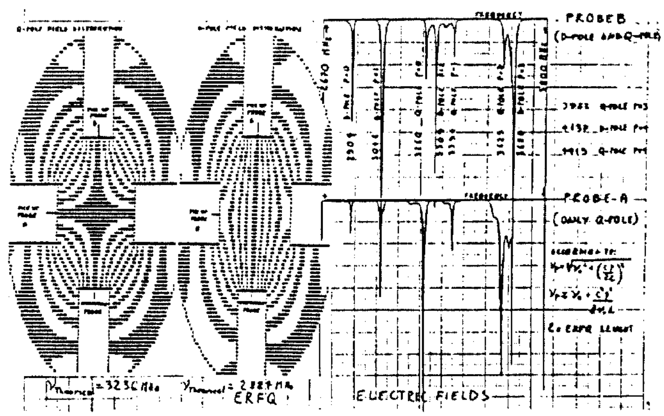


Figure 7

Conclusions

We presented in this note a study of feasibility of a RFQ for electrons with good characteristics to be used as an injector in a linac. This study is preliminary and will be followed by a more accurate study in order to reach minimum emittances with high peak current.

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