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# DETERMINATION OF OPTICAL PROPERTIES OF A FIELD EMISSION GUN COUPLED WITH A LINEAR ACCELERATOR FOR HIGH VOLTAGE MICROSCOPY

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## Abstract

The electron optical properties of a field emission gun plus a twenty-stage linear accelerator system have been determined in the case where the entrance pupil of the system is defined by one of the electrode apertures.

The first part of the calculation concerns the electrical and geometrical parameters of triode and tetrode field emission guns which can give a fixed location of the source and a small spherical aberration coefficient.

The second part is related to the possibility of placing a tetrode field emission gun at the top of the linear accelerator of the scanning high voltage electron microscope which is being constructed in the Toulouse Laboratory. Interesting conditions can be obtained when the electrical parameters are fixed as follows : either $V_i/V_e = 0$ or $V_i/V_e = 20$ ($V_e$ is the extracting voltage, $V_i$ is the potential of the second anode of the gun) whatever the accelerating voltage may be.

KEY WORDS : Field emission, Field emission guns, High voltage electron microscopy.

## Introduction

The electron optical properties of field emission sources and their advantages in conventional transmission electron microscopy as well as in scanning electron microscopy are now well known (Kasper, 1982). The Toulouse Laboratory being concerned with the construction of a high voltage scanning transmission electron microscope (named M.E.B.A.H.T. : Microscope Electronique à Balayage à Haute Tension) operating at 1.6 MV, there has been some interest in the problems of placing a field emission gun (F.E.G.) at the top of a linear accelerator.

Two approaches (Denizart et al. 1981 ; Garg et al. 1984) have been used to find an optimal configuration compatible with the requirements of field emission and high voltage (1.6 MV). We report here the results of our approach.

The study has been concerned with two questions : 1) Is it possible to design a gun-accelerator system such that the source position is unchanged when the beam current or the electron energy is varied ? 2) Can the diameter of the source obtained with such a system be kept sufficiently small to provide a good resolution in the M.E.B.A.H.T. ?

In a first stage, the electron optical properties of the F.E.G. have been studied, and the electrical and geometrical parameters giving a stable position and a small diameter of the effective source have been determined. In the following stage, the best gun geometry was used to determine the geometrical parameters of the accelerator and the electrical parameters of the gun-accelerator system.

Throughout this study, we have striven to find solutions that are simple from a technological point of view and flexible from the practical point of view. A triode F.E.G. was thus designed and tested in an electron microscope and the lessons which have emerged from its use induced us to study the optical properties of a tetrode F.E.G.

The results of a systematic study of the electron optical properties of triode and tetrode guns and of a tetrode F.E.G. + a twenty-stage linear accelerator system, are presented in this paper.

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## List of symbols

| | |
|---|---|
| $C_{so}$ | spherical aberration coefficient referred to the object space. |
| $C_{co}$ | chromatic aberration coefficient referred to the object space. |
| $M_L$ | linear magnification. |
| $Z_i$ | source position referred to the origin defined on fig. 1. |
| $V_a$ | acceleration voltage for the guns. |
| $V_e$ | extracting voltage. |
| k | ratio of $V_a$ to $V_e$ for a triode gun. |
| $V_i$ | potential of the intermediate anode of the tetrode guns. |
| $k_1$ | ratio of $V_i$ to $V_e$. |
| $k_2$ | ratio of $V_a$ to $V_e$ for a tetrode gun. |
| $V_1, \ldots V_{20}$ | potential of the first,... twentieth electrode of the accelerator. |
| $E_1, \ldots, E_{20}$ | first,..., twentieth electrode of the accelerator. |
| $A_1$ | first anode of a gun. |
| $A_2$ | second anode of a gun. |
| $A_3$ | third anode of a tetrode gun. |
| $D_{A_1A_2}$ | distance between the anodes $A_1$ and $A_2$. |
| e | thickness of the first anode in the triode guns. |
| $\alpha$ | cone angle of the aperture in the anode $A_1$ of a triode gun. |
| $D_{CA}$ | distance between the cathode and the first anode $A_1$. |
| $e_1, e_2, e_3$ | thickness of $A_1$, $A_2$, $A_3$ in a tetrode gun. |
| $\phi_1, \phi_2, \phi_3$ | diameters of the aperture of $A_1$, $A_2$, $A_3$ in a tetrode gun. |
| $\beta_1, \beta_3$ | cone angle of the apertures in the anodes $A_1$ and $A_3$ of a tetrode gun. |
| $e_E$ | thickness of the accelerator electrodes. |
| R | radius of the electrode apertures. |
| $f_o$ | object focal length. |
| $f_i$ | image focal length. |

## Generalities

The three types of systems studied are shown in fig. 1. We have only considered the case in which the entrance pupil of the system under study is defined by one of the electrode apertures : the best geometrical configuration will then be the one which has the smallest spherical and chromatic aberration coefficients $C_{so}$ and $C_{co}$ (referred to the object space) for any linear magnification $M_L$ (Denizart, 1981 ; Munro, 1971).

We have therefore examined the influence of the different geometrical parameters (the electrode thickness, the radius and the shape of the electrode aperture, the distance between the electrodes and between the tip and the first anode) on the position of the source (denoted by $Z_i = OS_i$ (fig. 1) and on the values of $C_{so}$, $C_{co}$ and $M_L$.

The purpose of the study was not to establish the exact properties of a small number of systems but to define the general characteristics of systems capable of giving a source stable in position and small in radius whatever the working conditions of the M.E.B.A.H.T. may be. A systematic study of many systems was therefore necessary.

The determination of the electron optical properties of an electrostatic system requires a knowledge of the potential distribution throughout the system. In view of the large number of geometries to be studied, it was not possible to take into account the real potential distribution between the tip and the first anode, although this can be calculated using the methods proposed by the different authors such as Kern et al. (1978), Hoch et al. (1978) or more recently by Kang et al. (1983) or Uchikawa et al. (1983). For this study, the space between the tip and the first anode has been considered to be equipotential. The finite element method has been employed to determine the potential using the program of Munro (1971), which has been adapted to obtain the electron optical properties of each system.

We note that by using different methods for calculating the properties of F.E.G., the discrepancies for the same gun between the finite element method and that of Kern can be shown to be quite acceptable, compared to the experimental precision (Denizart, 1981).

For the triode F.E.G., the properties are commonly studied as functions of a single electrical parameter $k = V_a/V_e$ ($V_e$ is the extracting voltage and $V_a$ the accelerating voltage). It has been shown (Denizart et al. 1981) that it is possible to characterize the properties of a tetrode F.E.G. as well as those of a tetrode F.E.G. + a twenty stage linear accelerator system in terms of two independent electrical parameters : $k_1 = V_i/V_e$ and $k_2 = V_a/V_e$ ($V_i$ is the potential of the intermediate anode $A_2$ and $V_a$ the accelerating potential of the tetrode F.E.G. (fig. 1b), furthermore $V_a = V_1 = V_{20}/20$ in the case of the complete system, $V_{20}$ being the accelerating voltage of the system (fig. 1c).

The principal results of the study are presented for each system as functions of the geometrical and electrical parameters that have been previously defined.

## Triode Field Emission Guns

Two types of triode guns have been considered : symmetrical ($A_1$ and $A_2$ are identical) and unsymmetrical ($A_1$ is the same as in the preceding case but $A_2$ is plane and 1 mm thick) (fig. 1a).

The thickness has been varied between 1 mm and 8 mm, the distance $D_{A_1A_2}$ between 3 and 12 mm, the cone angle of the anode aperture between 20° and 90° and the cathode-anode distance $D_{CA}$ between 4 and 12 mm.

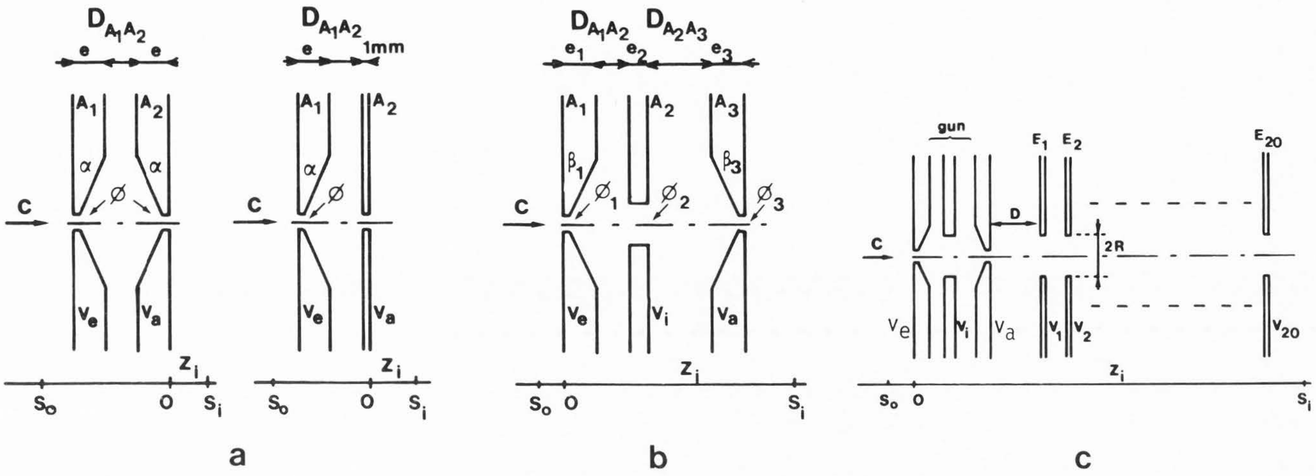


Fig. 1. Electrical and geometrical parameters of a triode gun (a), of a tetrode gun (b) and of a tetrode plus accelerator system (c).

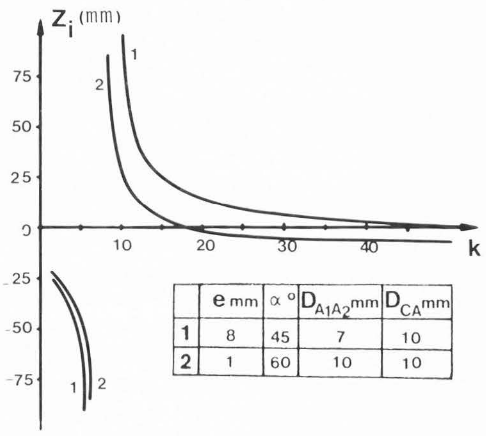


Fig. 2. Typical variation $Z_i = Z_i(k)$.

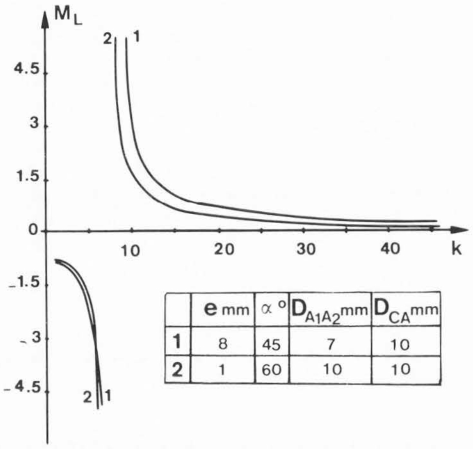


Fig. 3. Typical variation $M_L = M_L(k)$.

From a general point of view, it can be said that the best results are obtained with the unsymmetrical geometries and that the values of $C_{co}$ are 100 to 1000 times smaller than those of $C_{so}$, so only the results concerning the unsymmetrical systems and $C_{so}$ are given here.

We first consider the problem of the source position stability ; the curves plotted in fig. 2 give an example of the variation of $Z_i$ as a function of k. They show a discontinuity, the position of which depends on the geometrical parameters under consideration ($e, \alpha, D_{A_1A_2}, D_{CA}$), as do the $M_L$ curves shown in fig. 3. Thus flexible operating conditions of the gun and therefore of the microscope will not be obtained for k values lower than about 15. It will thus be necessary to choose working conditions such that $k > 15$ and $30$ kV $< V_a <$ $80$ kV, which corresponds to the condition $V_e < 2$kV. These can be satisfied with short $D_{CA}$ distances or with good tips (Denizart, 1981).

Furthermore, the study shows that $Z_i$ is less sensitive to k if α and $D_{CA}$ are large - but if $D_{CA}$ is large $V_e$ cannot be kept sufficiently low - and e and $D_{A_1A_2}$ small. So if $D_{A_1A_2}$ has to be as small as possible for each value of $V_a$, it will be necessary to modify the $D_{A_1A_2}$ distance in vacuum and under tension, to avoid breakdown problems between the anodes. Even, if this can be done on an experimental low voltage gun, it is not realistic on the M.E.B.A.H.T.

Thus, if only the problem of the source position stability is considered a geometry such as $\alpha \simeq 60°$, $e \simeq 1$ mm, $D_{A_1A_2} = 1$ mm would give good results for $V_a > 50$ kV that is to say for $k > 20$.

Furthermore, the choice of the best geometry has to take into account the values of $C_{so}$ and the variations of $Z_i$ which have to be, at the same time, as small as possible. As we are considering the case where the entrance pupil is defined by the conjugate of one of the anodes, the study shows that, whatever the linear magnification $M_L$ may be, the geometry that gives the smallest values of $C_{so}$ is such that $\alpha \simeq 45°$, $e \simeq 8$ mm, $D_{A_1A_2} \simeq 7$ mm and $D_{CA} = 10$ mm (fig. 4).

Furthermore, as can be seen in fig. 2, the source position stability is quite acceptable for this last configuration if k is chosen greater than 20.

This gun geometry has been built and adapted on a microscope (Denizart, 1981 and Denizart et al. 1981) and it has been possible to obtain a source for which the transverse coherence length determined by the Young's holes method (Munch, 1975 ; Denizart, 1981) is 0.6 µm.

Nevertheless, such a gun is not suitable for an adaptation to the M.E.B.A.H.T. accelerator especially considering the life-time problem created by the poor protection of the tip against breakdown. For this reason, a similar study of the behaviour of the tetrode F.E.G. has been made.

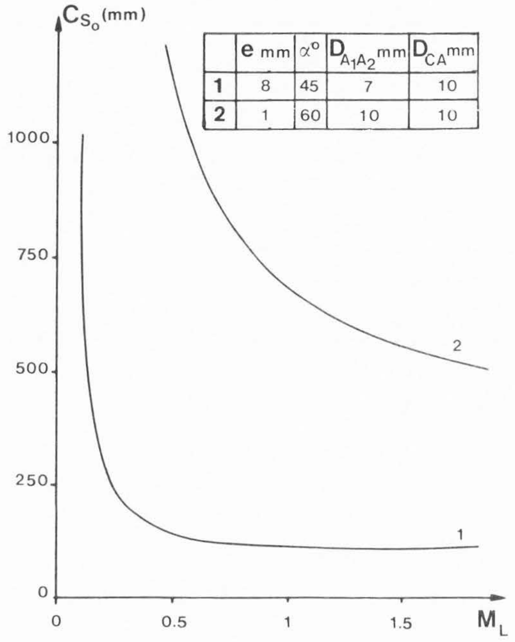
## Tetrode Field Emission Guns

Since the optical properties of the tetrode gun can be defined in terms of two independent electrical parameters $k_1 = V_i/V_e$ and $k_2 = V_a/V_e$, the influence of each geometrical parameter on the source position and on the aberration coefficients has been studied as a function of $k_1$ and $k_2$.

The study has covered the following ranges of the electrical and geometrical parameters : $0 < k_1 < 25$, $5 < k_2 < 50$ and $1 \text{ mm} < e_2 < 6$ mm, $1 \text{ mm} < \phi_2 < 6$ mm, $35° < \beta_1 = \beta_3 < 60°$, $1 \text{ mm} < \phi_1 = \phi_3 < 6$ mm, $3 \text{ mm} < e_1 = e_2 < 10$ mm, $3 \text{ mm} < D_{A_1A_2} < 10$ mm and $5 \text{ mm} < D_{CA} < 10$ mm. We set out from an initial geometry derived from the results obtained for the triode guns and from the preliminary studies. This geometry is such that : $e_1 = e_3 = 4$ mm, $\phi_1 = \phi_3 = 1$ mm, $e_2 = 2$ mm, $\phi_2 = 3$ mm and $\beta_1 = 45°$.

The values of $k_1$ that give a stable position of the source, whatever $k_2$ may be, are $k_1 = 0$ and $k_1 > 15$. If $0 \lesssim k_1 \lesssim 7$, the curves $Z_i(k_2)$ may exhibit discontinuities (fig. 5a). It can be seen that for $k_1 > 15$, $C_{so}$ takes constant and small values but for $k_1 = 0$, $C_{so}$ is greater than $10^4$ mm and has not been indicated on fig. 5b. Furthermore, the corresponding values of the linear magnification $M_L$ cannot compensate the values of $C_{so}$ (fig. 5c).

In spite of the poor $C_{so}$ value obtained for $k_1 = 0$, we have considered this case in the following ; it is of practical interest due to the tip protection it can provide against the breakdown phenomena (Engel and Sauer, 1979).



| | e mm | $\alpha°$ | $D_{A_1A_2}$ mm | $D_{CA}$ mm |
|---|---|---|---|---|
| **1** | 8 | 45 | 7 | 10 |
| **2** | 1 | 60 | 10 | 10 |

Fig. 4. Typical variation $C_{so} = C_{so}(M_L)$.

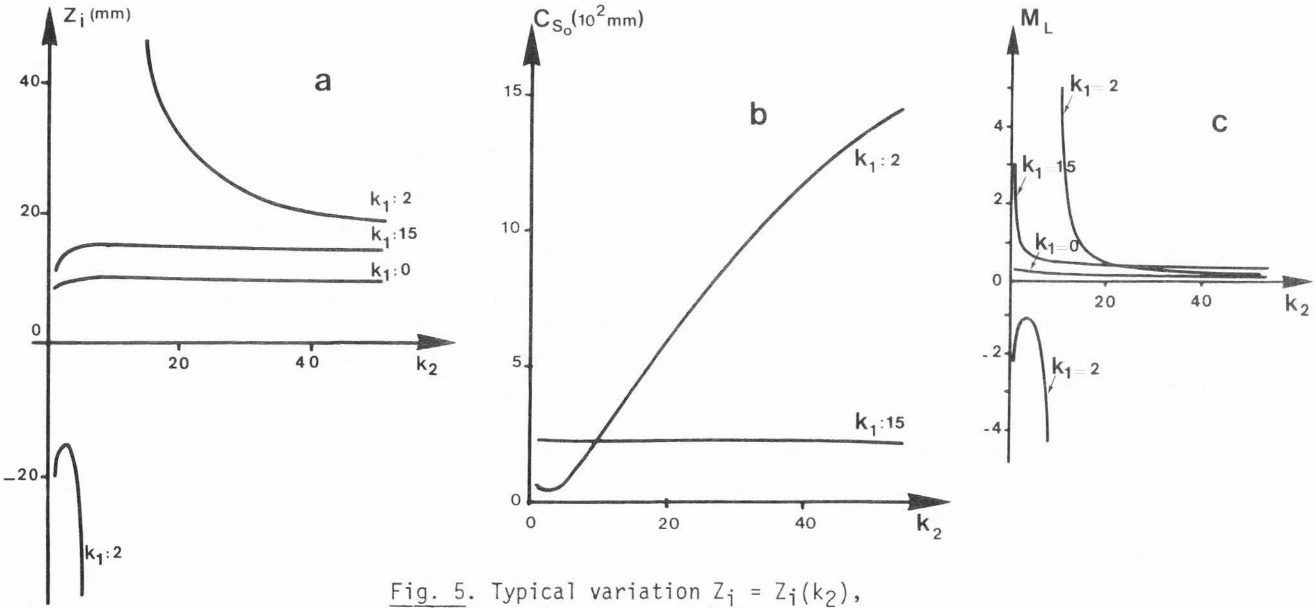


Fig. 5. Typical variation $Z_i = Z_i(k_2)$, $C_{so} = C_{so}(k_2)$ and $M_L = M_L(k_2)$. Parameter $k_1$.

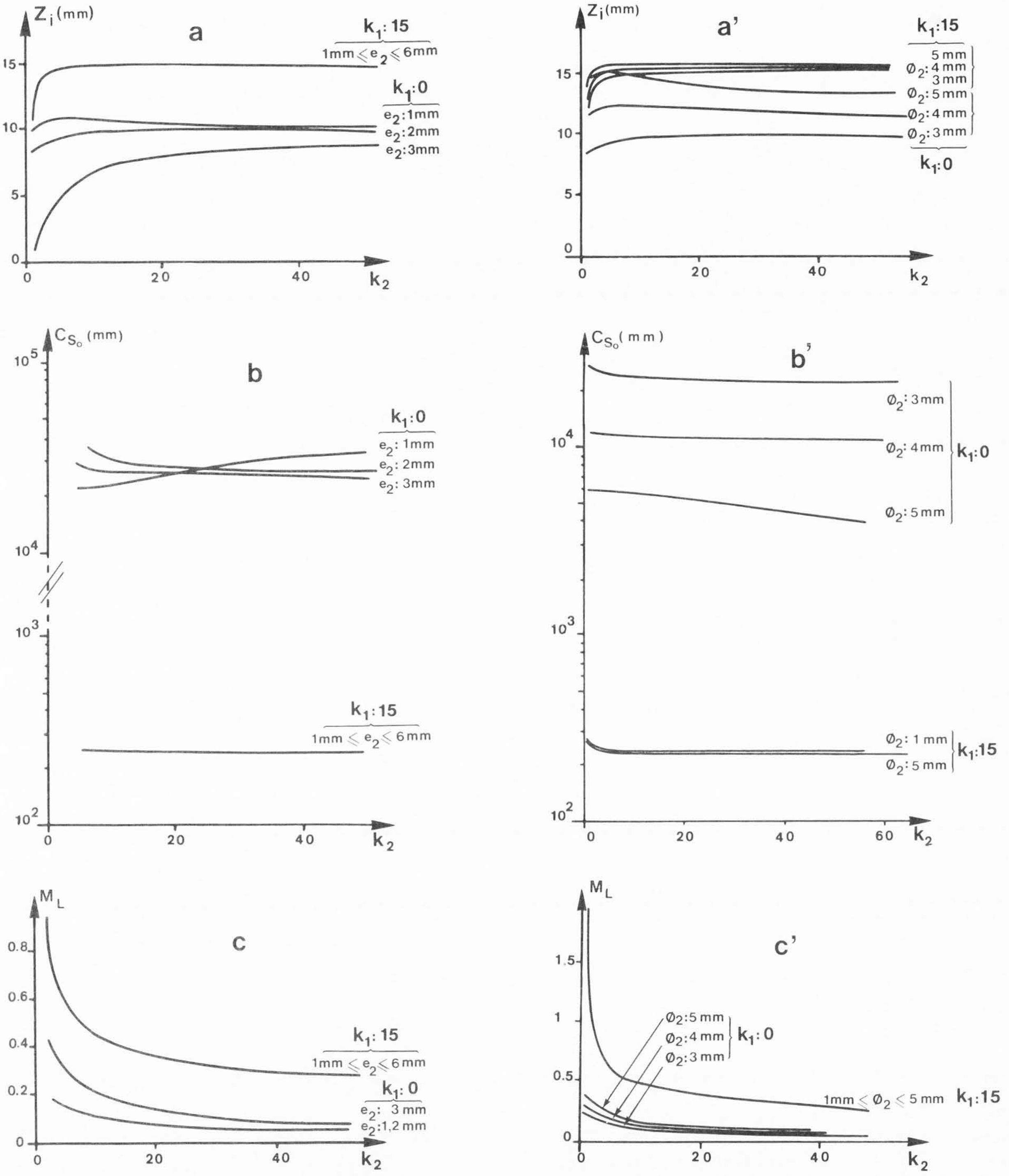


Fig. 6. Variation of $Z_i$, $C_{so}$, $M_L$ as functions of $k_2$ for $k_1 = 0$ and $k_1 = 15$. Parameter $e_2$ (a,b,c) and $\phi_2$ (a',b',c').

In a first stage, the geometrical parameters of the intermediate anode $A_2$ have been studied. The best results correspond to 3 mm $< \phi_2 <$ 5 mm and 1 mm $< e_2 <$ 3 mm for $k_1 = 0$ and $k_1 > 15$, but the values of $C_{so}$ are always very large for $k_1 = 0$ and not compensated by $M_L$. For $k_1 > 15$, $Z_i$, $C_{so}$ and $M_L$ are less sensitive to the variations of $e_2$ and $\phi_2$ than for $k_1 = 0$ (fig. 6).

In a second stage, taking $e_2 = 2$ mm and $\phi_2 = 4$ mm, the influence of the geometrical parameters of $A_1$ and $A_3$ have been studied. A preliminary study of some geometries where $A_3$ was plane showed that the stability of the source position was poor, particularly for $k_1 = 0$, and we have therefore considered the case where $A_1$ and $A_3$ are the same (fig. 1b) and we put : $\phi_1 = \phi_3 = \phi$, $e_1 = e_3 = e$ and $\beta_1 = \beta_3 = \beta$. From the study, we draw the following conclusions :

- the angle $\beta$ has practically no influence on the optical properties of the tetrode gun particularly for $k_1 = 0$, while $C_{so}$ is always about $3.10^4$ mm. For $k_1 > 15$, $Z_i$, $C_{so}$, $M_L$ vary slowly and the smallest $C_{so}$ is obtained for $\beta = 48°$.
- the diameter $\phi$ does not affect $Z_i$ and $M_L$ and $C_{so}$ increases with $\phi$ for $k_1 = 0$. The same is true for $k_1 = 15$ if $\phi < 3$ mm.
- the thickness e has a greater influence on the optical properties than $\beta$ or $\phi$ but the corresponding variations do not strongly modify these properties. The best values are obtained for $e \simeq 4$ mm.
- the distance $D_{A_1A_2}$ has the same type of influence as e and taking into account the breakdown problems between the anodes, it seems reasonable to choose 4 mm $< D_{A_1A_2} <$ 5 mm.

A "best geometry" would thus be such that : $\phi = 1$ mm, $e = 4$ mm, $\beta = 48°$, $\phi_2 = 4$ mm, $e_2 = 2$ mm, $D_{A_1A_2} = 4$ mm and $D_{A_2A_3} = 10$ mm.

Concerning the influence of $D_{CA}$, it can be said that if the geometry is the "best" one, the variations of $D_{CA}$ have no influence on the properties of the gun ; this is not true if the geometrical parameters do not have the optimal values and discontinuities appear in the $Z_i(k_2)$ curves.

All the properties which have been calculated for the "best geometry" are summarized on fig. 7a for $k_1 = 0$ and on fig. 7b for $k_1 = 15$. It is this geometry which has been chosen for our study of the optical properties of an F.E.G. + a linear accelerator.

## Tetrode Field Emission Gun Plus Twenty-Stage Linear Accelerator System

Taking into account the technological constraints related to the construction of the electrodes of the accelerator, we have considered plane electrodes.

The study covers electrical parameters in the ranges $0 < k_1 < 30$ ($k_1 = V_i/V_e$) and $0 < k_2 < 100$ ($k_2 = V_a/V_e = (V_{20}/V_e)/20$) and geometrical parameters in the ranges 1 mm $< e_E <$ 10 mm, 2.5 mm $< R <$ 60 mm and 5 mm $< D_{CA} <$ 10 mm. The distance d between electrodes is taken to 50.5 mm, which is the lower limit for a maximum potential difference of 80 kV and the distance D (fig. 1c) between the third anode ($A_3$) of the gun and the first electrode ($E_1$) of the accelerator has been determined in such a way that the accelerator field does not perturb the field in the gun and hence the optical properties of this gun. The optimal value of D is 40 mm.

Concerning the source stability problem, an example of the results obtained for all the configurations which have been studied is shown in fig. 8 for two values of $D_{CA}$. A stable position of the source is obtained for $k_1 = 0$ and $k_1 > 20$ whatever $k_2$ may be. For $k_1 = 15$ and $D_{CA} = 10$ mm, the source stability is good but is not satisfactory for $D_{CA} = 5$ mm.

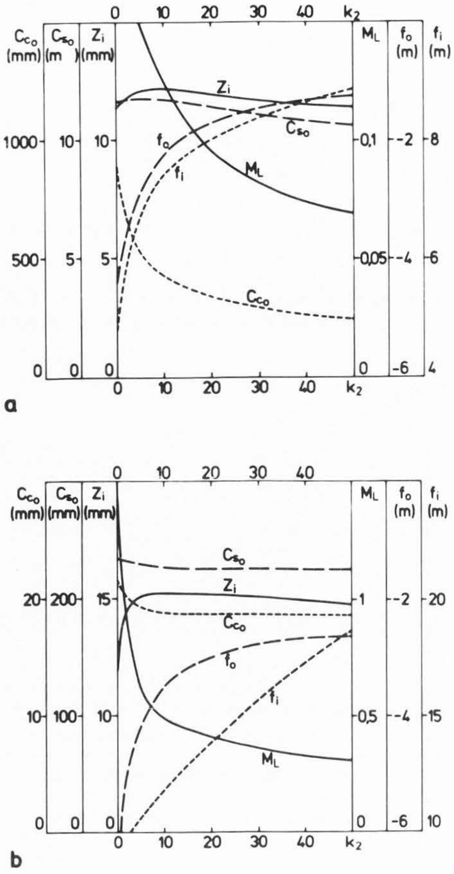


Fig. 7. Variation of $Z_i$, $C_{so}$, $C_{co}$, $M_L$, $f_o$ and $f_i$ as a function of $k_2$ ; for $k_1 = 0$ (a) and $k_1 = 15$ (b).

Turning to the variations of $C_{so}$, it can be seen (fig. 9) that for $k_1 = 0$, the very large values taken by $C_{so}$ are not compensated by the linear magnification. On the other hand for $k_1 = 20$, $D_{CA} = 5$ mm and $R > 7.5$ mm the values of $C_{so}$ lie between 20 and 50 mm. Giving priority to the source position stability, $k_1$ must be taken between 15 and 20 and $D_{CA} = 5$ mm.

The electrical parameters now being determined, the influence of $e_E$ and R on $Z_i$ and $C_{so}$ has been studied and the smallest variations $\Delta Z_i$ of $Z_i$ are obtained for $k_1 = 20$, $D_{CA} = 10$ mm, R = 10 mm and $e_E < 3$ mm. For these values, $\Delta Z_i \simeq 1.4$ mm if $10 < k_2 < 90$ and $\Delta Z_i \simeq 0.4$ mm if $10 < k_2 < 50$ (figs. 10a and 10b).

An example of the $C_{so}$ variations as a function of R is shown in fig. 9 for $k_2 = 50$, $k_1 = 0,20$ and $D_{CA} = 5,10$ mm, the thickness being 1 mm. The smallest $C_{so}$ (and the greatest $M_L$) correspond to $k_1 = 20$ and $D_{CA} = 5$ mm whatever R may be. However, as shown in Table 1, $M_L$ cannot compensate the great values taken by $C_{so}$ for $k_1 = 0$.

Note also that for $k_1 = 20$ and $D_{CA} = 5$ mm, $C_{so}$ is constant for $R > 7.5$ mm if $e_E = 1$ mm, $R > 15$ mm if $e_E = 3$ mm and $R > 30$ mm if $e_E = 10$ mm. Furthermore $C_{so}$ is not very sensitive to $k_2$ for $R > 5$ mm.

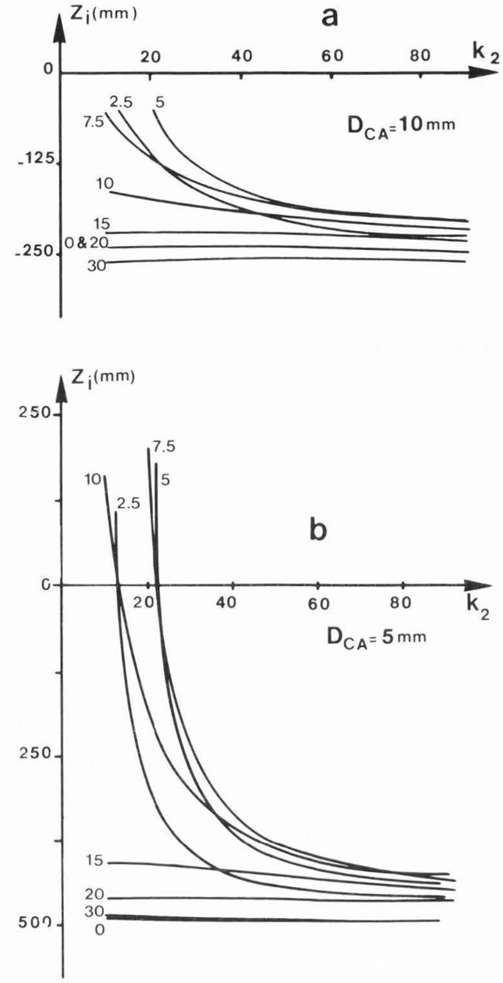


Fig. 8. Typical variation $Z_i = Zi(k_2)$ for $D_{CA}$ = 10 mm (a) and $D_{CA}$ = 5 mm (b). Parameter R (mm).

| $k_1$ | $D_{CA}$ mm | $C_{so}$ mm | $M_L$ |
|---|---|---|---|
| 0 | 5 | 9.5 $10^3$ | 0.09 |
|  | 10 | 3.4 $10^4$ | 0.06 |
| 20 | 5 | 36 | 0.8 |
|  | 10 | 80 | 0.25 |

Table 1. Typical values of $C_{so}$ and $M_L$ for $k_1$ = 0,20 and $D_{CA}$ = 5,10 mm.

We recall finally that $C_{co}$ is always 100 to 1000 times smaller than $C_{so}$. It thus seems reasonable to regard following geometrical parameters of the accelerator electrodes as the best that can be achieved : 10 mm < R < 15 mm and $e_E \simeq 1$ mm.

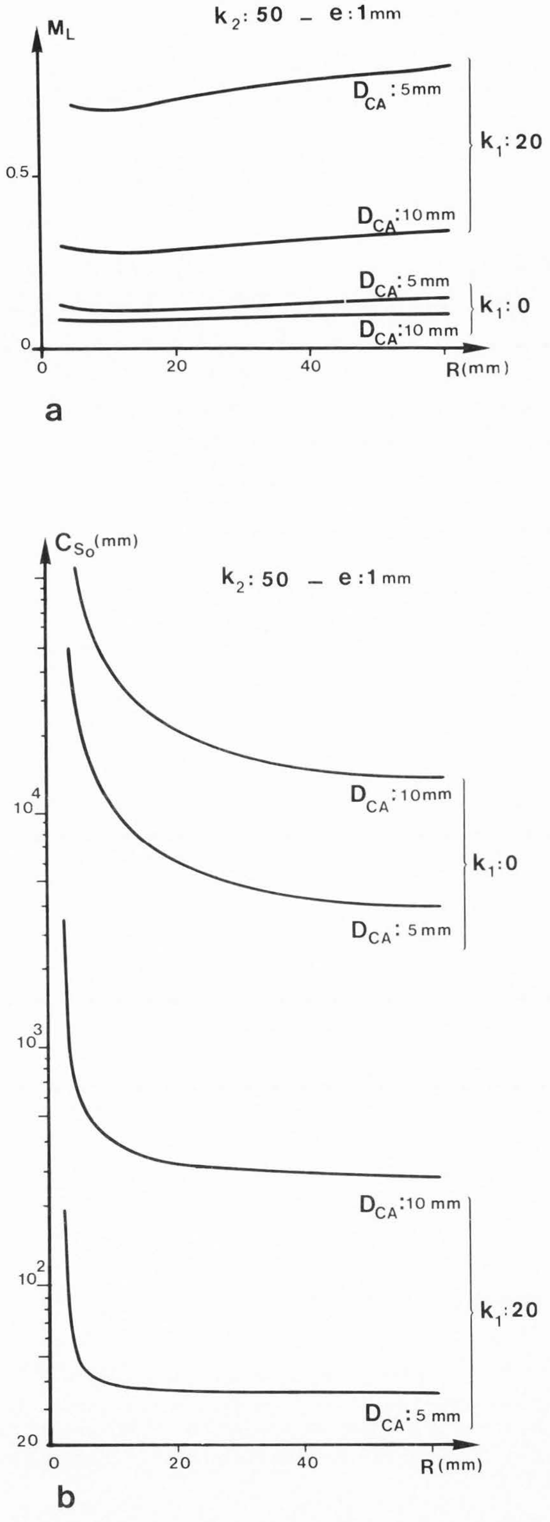
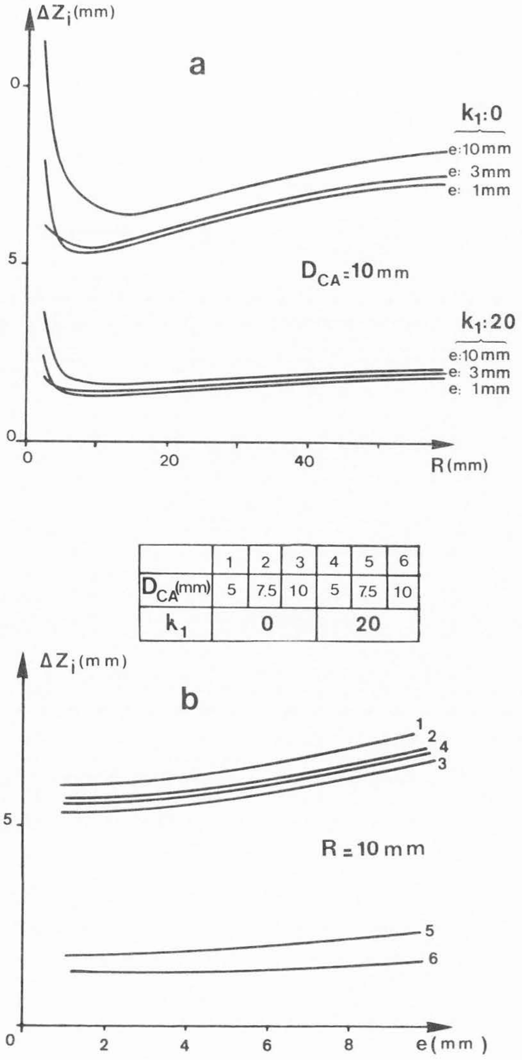


Fig. 9. Variation of $M_L$ (a) and $C_{so}$ (b) as function of R for e = 1 mm, $k_2$ = 50, $k_1$ = 0.20 and $D_{CA}$ = 5.10 mm.



| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $D_{CA}$(mm) | 5 | 7.5 | 10 | 5 | 7.5 | 10 |
| $k_1$ | 0 | | | 20 | | |

Fig. 10. Variation of the source position as a function of R (a) and as a function e (b) for $k_1$ = 0.20.

## Conclusion

The results given above form part of a study of the gun plus linear accelerator system for the Toulouse 1.6 MV (M.E.B.A.H.T.). They show that it should be possible to obtain a perfectly stable position of the source.

The radius of the source will lie between 200 and 800 nm for $V_e$ = 1 kV, $k_1$ = 15, $D_{CA}$ = 5 mm and between 150 and 300 nm for $V_e$ = 3 kV, $k_1$ = 15, $D_{CA}$ = 5 mm. These values could be reduced by introducing a diaphragm between the gun and the accelerator. The determination of the characteristics of a system with such an aperture is the main object of our present work.

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## Discussion with Reviewers

J. Orloff: The readers may be interested in the following references which are relevant to the topic of this paper:

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Authors: Thank you.