Laboratori Nazionali di Frascati

LNF-87/98(R)
16 Novembre 1987

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A GUN FOR LISA

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1. - INTRODUCTION

Recently in the LNF it was proposed to construct LISA: a superconducting electron linac which will be able to give high peak currents (10 A) with low emittance ($\varepsilon \leq \pi 10^{-5}$ m$*$Rad), small energy dispersion ($\Delta w/w \leq 2\ 10^{-3}$) and energy of 20÷30 MeV.

The aims of this project together with main parameters are given in [1,2,3].

One of the most important elements which determines the quality of the beam of accelerated electrons is the injection system and particularly the source of electrons-the gun.

The basic requirements for the gun were specified in [2] and are reassumed below for further considerations:

CURRENT	I= (0.1÷0.2) A
ENERGY	W = 100KeV
ENERGY DISPERSION	$\Delta W/W = 10^{-4}$ (10^{-3})
EMITTANCE (INVAR.)	$\varepsilon \leq \pi\ 10^{-5}$ m$*$ Rad

To fulfill the above requirements an optimization study of modified PIERCE geometry of the gun has been undertaken at LNF. The goal was to obtain either parallel or slightly convergent beam

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with long focal distance (~100 mm) and a small focal spot (radius < 0.5 mm) which can be then easily transported with the aid of a system of magnetic lenses. We would like also to have the possibility of pulsing the gun varying both the pulse length and repetition rate. This requires to use the gun with control grid. The results of this study are presented below.

2. - CHOICE OF THE GEOMETRY

The geometry of most electron guns has been evolved from that found analytically by PIERCE [4,5] and is usually called the Pierce type geometry. Strictly speaking this geometry was found for a planar space-charge-limited electron beam (planar space-charge-limited diode). Pierce showed that the effect of the electrons external to some chosen region of parallel flow could be represented by means of a single unipotential electrode called the 'beam forming or focusing electrode'. Near the cathode edge the focusing electrode is displaced at an angle of 67.5^0 from the beam edge .

This shape assures the correct distribution of surface charges and therefore electric flux lines in the charge free region so as to satisfy the boundary conditions at the beam. As a result the electrons in the beam still behave as though they were flowing in the complete diode, that is they pursue rectilinear trajectories.

In other gun geometries (eg. cylindrical, spherical, etc.) the region immediately adjacent to the cathode edge can be considered as nearly planar so that this same design rule for the focus-electrode shape near the cathode is generally used in the most gun designs, and this kind of geometry is called the Pierce type geometry.

Strictly speaking, the Pierce design procedure tacitly assumes that the equipotential lines within the beam flow region including that in the vicinity of anode, are sectors of concentric spheres, (planes, cylinders etc.). This corresponds to the case without a hole in the anode allowing the beam to pass through it. The hole in the anode disturbs the electric field distribution so that the equipotential lines are no more parallel to the surface of the anode but are bend up into anode aperture.

The disturbation of the electric field is obviously proportional to the surface of the aperture which depends upon the extracted current or more precisely on the perveance

$$P = Ia * Ua^{-3/2}$$

where Ia is the current passing through the anode and Ua is the potential between anode and cathode. Usually the action of the anode aperture in the case of small perveance can be described by a thin electron lens with a focal length given by Davisson-Calbick equation [6,7]. The gun can be divided into 3 regions:

1) the region of the rectilinear flow, in which the Langmuir relations for space charge limited flow are used;
2) a thin electric aperture lens in the vicinity of the anode;
3) the emergent beam outside of the gun .

The detail of this analytical approach valid for low perveances-below 0.1 μ Perv, can be found eg. in Brewer [7]. No such simple analytical design procedure seems to exist for gun of higher perveance, and usually a numerical calculation approach is necessary. It consists in simultaneous solution of Maxwell Equations and equations of motion.

The external electric and magnetic fields are specified and the self-fields created by moving charged particles are determined. Particle trajectories are calculated in the sum of these fields, and from these trajectories the coherent self-fields are recalculated. The procedure is made self-consistent by iterating until stationary solution is obtained.

If the externally applied fields are not properly chosen, no stationary solution can be found.

One of the most frequently used numerical programs of this type for the calculation of electron gun is that of Hermannsfeldt SLAC Electron Trajectory Program [8]. This program is specifically written to compute trajectories of charged particles in electrostatic and magnetostatic systems including the effects of space-charge and self-magnetic fields.

Starting options includes Child's Law conditions on cathodes of various shapes. Below we will use this program to calculate the shapes of electrodes and the parameters of the electron gun for LISA.

As a starting geometry of the gun we will take that of PIERCE with modified focusing electrode in order to compensate the effect of the anode aperture and to have the possibility of changing the position and dimensions of the focal spot.

3. - NUMERICAL CALCULATION

3.1. - Starting Conditions

A schematic layout of geometry we would like to use for a gun is shown on Fig. 1.

The gun has the cylindrical symmetry. The following parameters have been constant during calculations:

Spherical radius of the cathode	R_k =40 mm
Cathode radius (height)	r_k =3.2 mm
Grid (concentric with cathode) thickness	d_g = 0.2 mm
Spherical radius of the grid	R_g = 39 mm
Anode hole	ϕ_a = 8 mm
Anode-conical ended with a sphere of radius	R_a = 2 mm

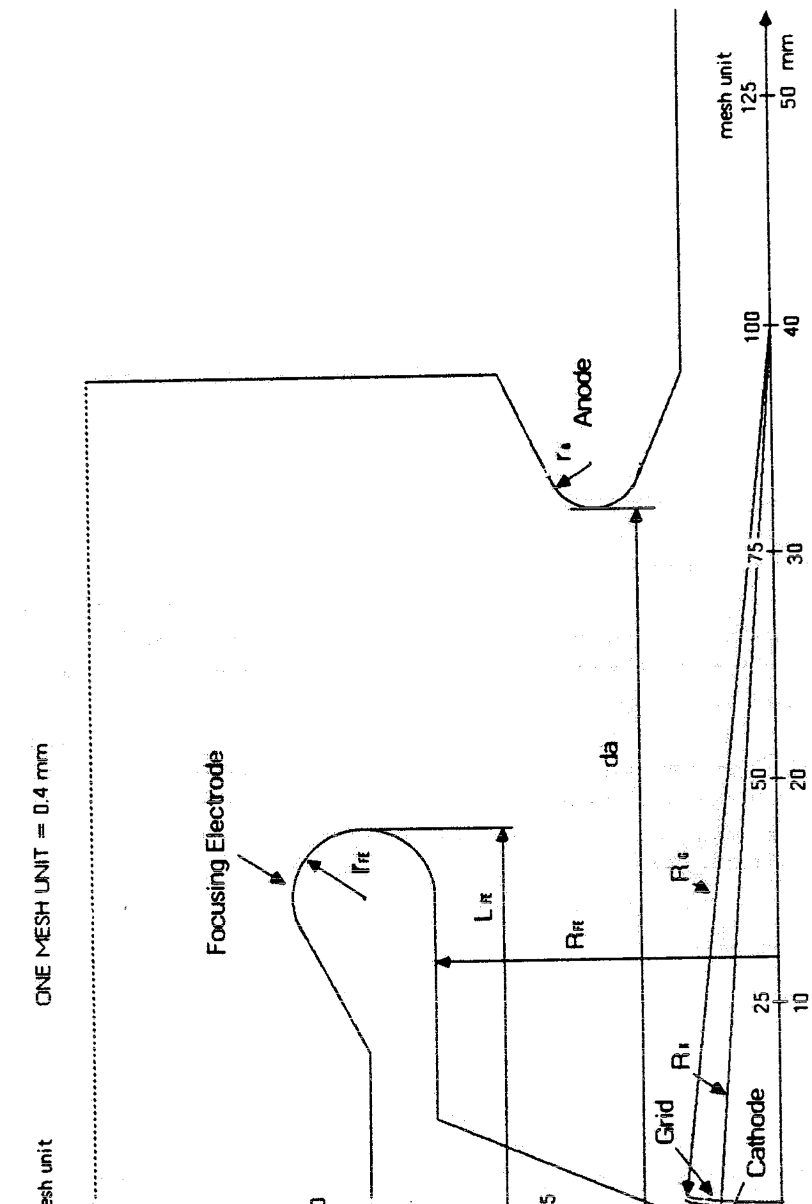


FIG. 1 — The geometry of the gun.

To avoid breakdown between the focusing electrode and anode the minimum distance between these two electrodes is always greater than 16÷17 mm.

To optimize the characteristic of the output electron beam the following geometric and electric parameters of the gun were variable:

radius of the focusing electrode	R_{fe} = (13 ÷ 18) mm
lenght of the focusing electrode	L_{fe} = (16.6 ÷ 18) mm
potential between anode and cathode	U_a = (90÷110) kV
potential of the grid	U_g = (225÷600) V
curvature radius of the foc. electrode	r_{fe} = (0.6÷3.0) mm

3.2. - Results and Discussion

The results of numerical calculations are presented on Figs. 2÷20 where the electron rays in the gun are traced, and in the Table I where the main parameters of the beam emerging from the gun are given as a function of gun geometry and anode and grid voltages. It is seen from this table that the beam parameters depend strongly on the diameter R_{fe} of the focusing electrode. E.g. the change of R_{fe} in the range (13÷18) mm causes variation of I_a from 0.47A to 1.180A ,the perveance from 0.015μP. to 0.037μP., the emittance from (1.3 to 2.41)$\pi * 10^{-6}$m*Rad, and the position of the waist of the beam from 48 mm to 94 mm . It means then that changing only R_{fe} one can match within rather wide limits the parameters of the beam to the requirements of the accelerating system. In our case of gun for LISA it seems that the choice of R_{fe}=15 mm is close to optimum. In fact it yields rather long focal distance equal to approximately 94 mm , which is convenient for use of magnetic focusing of the beam , sufficiently high current intensity of about 800 mA and low emittance of about $2.5 * \pi * 10^{-6}$ m*Rad. All these parameters are better than those required for LISA Gun.

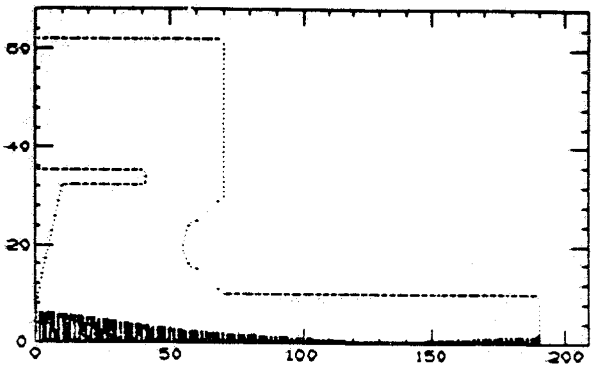


FIG 2

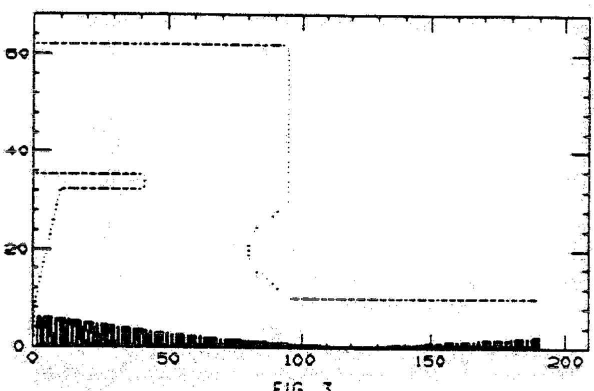


FIG 3

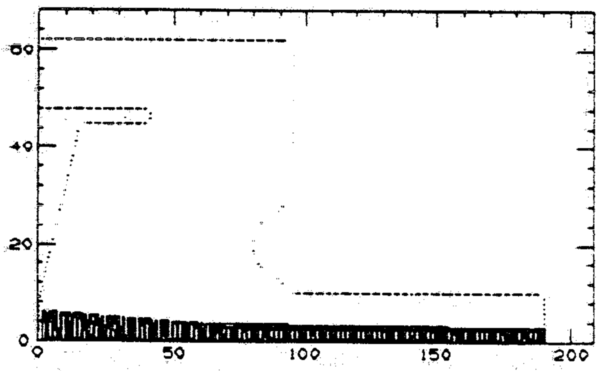


FIG 4

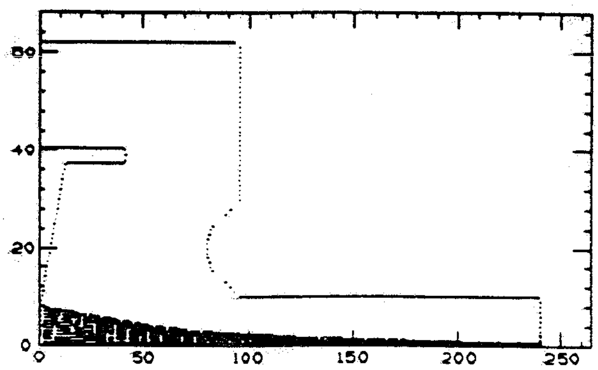
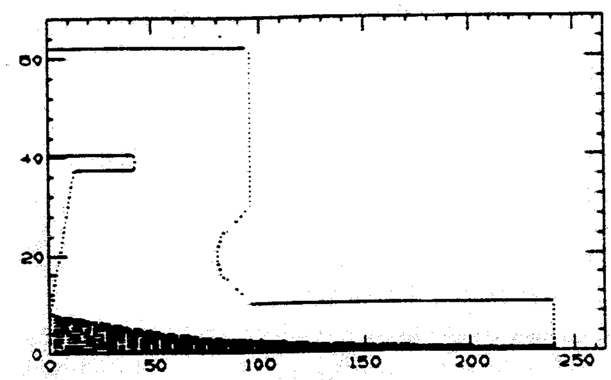


FIG 5



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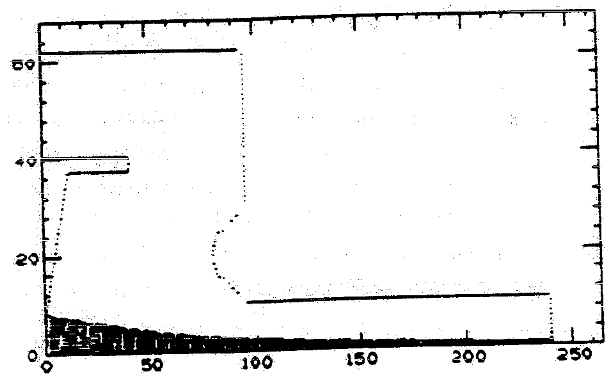

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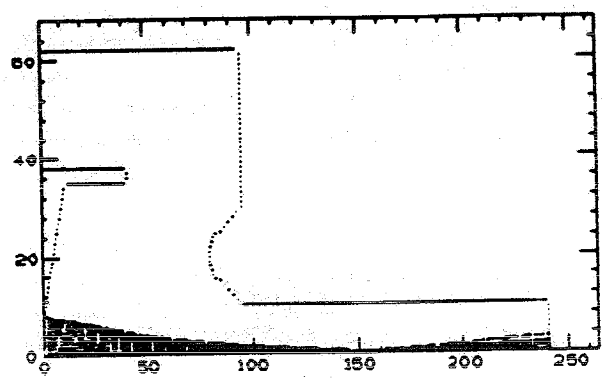


FIG. 8

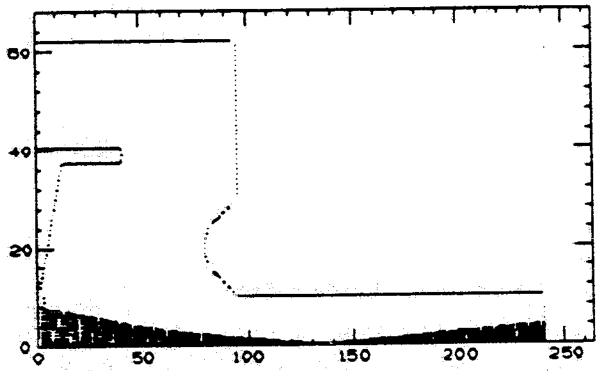


FIG 9

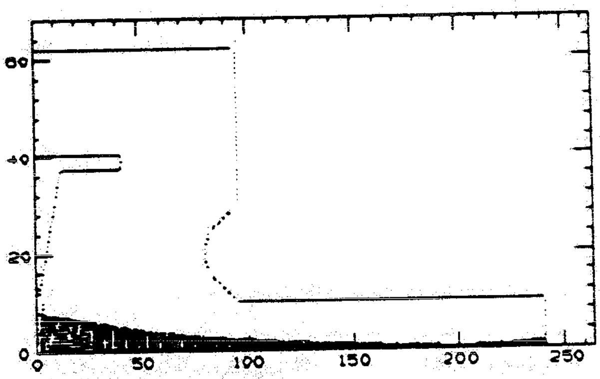


FIG 10

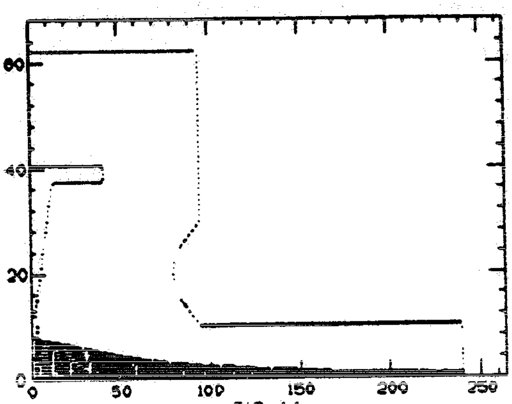
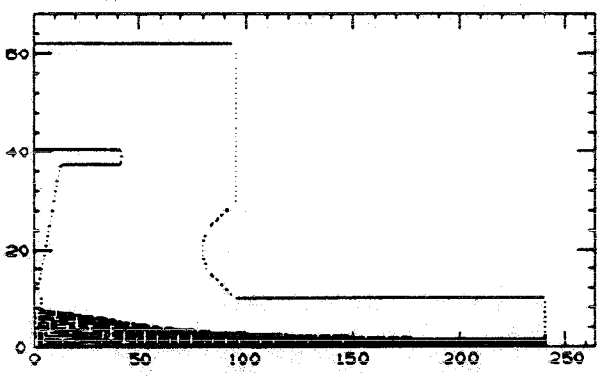


FIG 11



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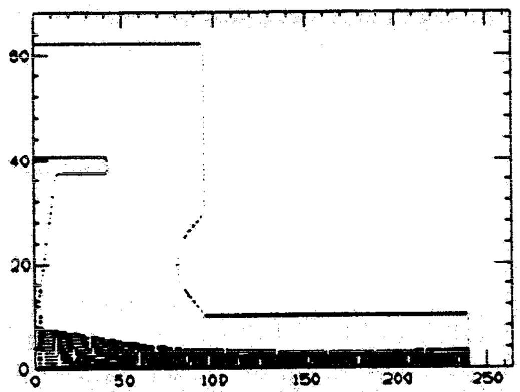

FIG 13

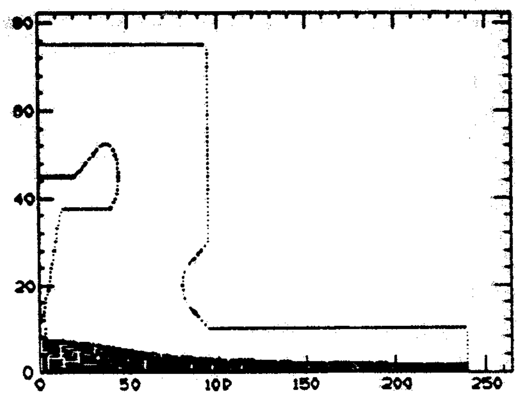

FIG 14

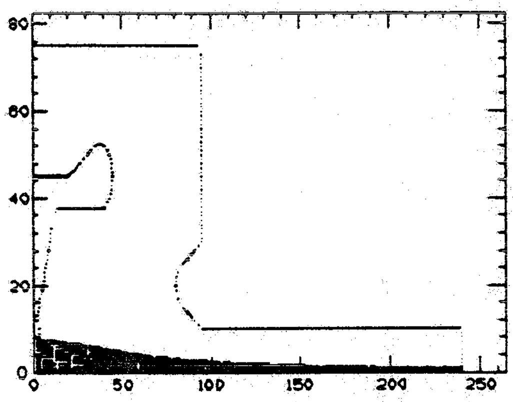

FIG. 15

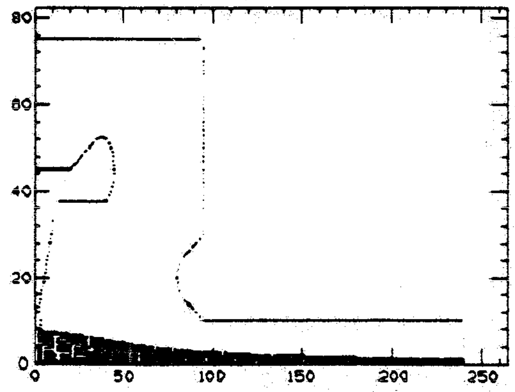

FIG 16

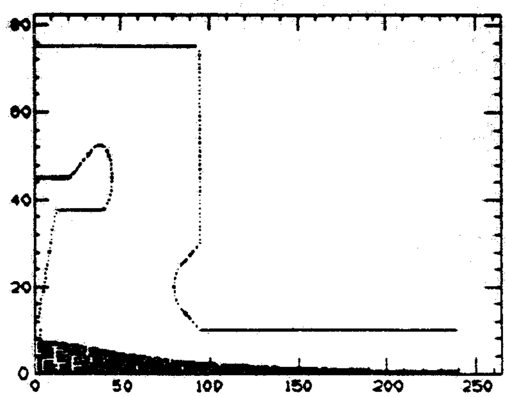

FIG 17

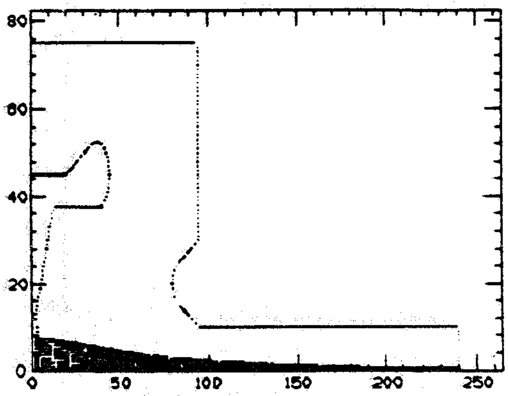

FIG 18

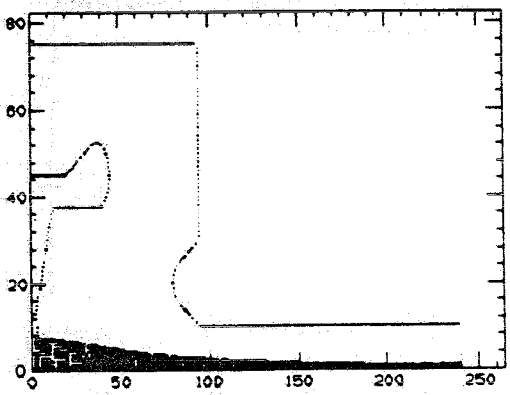

FIG 19

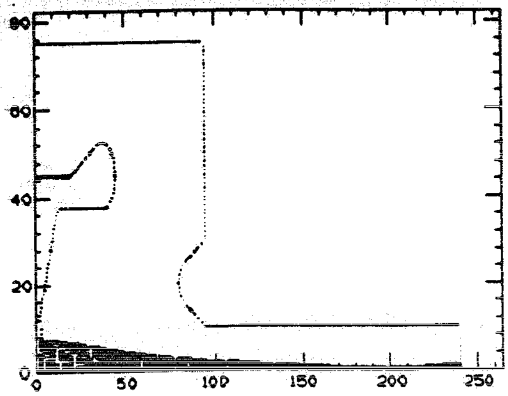

FIG 20

TABLE I

da	R_{FE}	L_{FE}	r_{FE}	Ua	Ug	Ia	$P=\frac{Ia}{Va^{3/2}}$	$\varepsilon*10^6$	R_{min}	Z_{min}	R_{end}	Z_{end}	Figure number
mm	mm	mm	mm	KV	KV	A	μPerv	π*m*Rad	mm	mm	mm	mm	
22.0	12.95	16.6	0.6	100	-	0.963	0.030	2.14	0.006	53	1.16	76.5	2
32.0	12.95	16.6	0.6	100	-	0.473	0.015	1.3	0.007	48	1.28	76.5	3
32.0	18.00	16.6	0.6	100	-	1.184	0.037	2.4	1.55	55	1.67	76.5	4
32.0	15.00	16.6	0.6	100	-	0.745	0.024	2.41	0.24	94	0.242	96.4	5
32.0	15.00	16.6	0.6	110	-	0.860	0.024	2.69	0.235	94	0.236	96.4	6
32.0	15.00	16.6	0.6	90	-	0.637	0.024	2.17	0.247	93	0.25	96.4	7
32.0	14.00	16.6	0.6	100	-	0.605	0.019	2.4	0.005	64	1.3	96.5	8
32.0	15.00	16.6	0.6	100	0.250	0.297	0.009	1.27	0.006	54	1.59	96.5	9
32.0	15.00	16.6	0.6	100	0.400	0.600	0.019	1.4	0.003	85	0.47	96.4	10
32.0	15.00	16.6	0.6	100	0.450	0.715	0.023	2.02	0.329	93.4	0.33	96.4	11
32.0	15.00	16.6	0.6	100	0.500	0.837	0.026	2.34	0.65	86	0.67	96.4	12
32.0	15.00	16.6	0.6	100	0.600	1.100	0.035	3.16	1.23	72	1.32	96.4	13
32.0	15.00	18.0	3.0	100	0.500	0.837	0.026	2.93	0.71	89	0.72	96.4	14
32.0	15.00	18.0	3.0	100	0.450	0.712	0.023	2.23	0.340	96	0.34	96.4	15
32.0	15.00	18.0	3.0	95	0.450	0.712	0.024	2.20	0.51	90	0.52	96.4	16
32.0	15.00	18.0	3.0	105	0.450	0.712	0.021	2.64	0.22	96	0.22	96.4	17
32.0	15.00	18.0	3.0	95	0.425	0.654	0.022	2.13	0.32	95	0.32	96.4	18
32.0	15.00	18.0	3.0	100	0.425	0.654	0.021	2.48	0.16	96.4	0.3	96.4	19
32.0	15.00	18.0	3.0	105	0.425	0.654	0.019	1.75	0.03	84	0.54	96.4	20

Another possibility of controlling the beam parameters is to use the grided gun , triode instead of diode.

By variation of the grid potential all the parameters of the beam can be changed as it is clearly seen in Fig. (9÷20) and in the Table I. The use of the triode will be also necessary in the case when the gun should be pulsed, as it was suggested above.

It follows from the Table I that for U_a =100kV the optimum potential of the grid is U_g = (425÷500)V. For these values of U_a and U_g the emerging beam is almost parallel, it has small radius between (0.3÷0.7) mm, small emittance $\varepsilon = 2.5*\pi*10^{-6}$ m*Rad. and sufficiently high current I_a = (0.65÷0.8) A.

It is interesting to note that the variations of the beam emittance are proportional to the changes of its perveance. This fact can be used to obtain some scale factor for emittance as a function of the perveance of the beam.

In order to get some information about the influence of the stability of the anode potential on the parameters of the beam few cases were calculated with variable U_a.

Three sets of calculations are made:

a) U_a= 90,100,110 kV, no grid, focusing electrode with R_{fe} =15 mm and r_{fe} =0.6 mm.

b) U_a =95,100,105 kV, U_g = 450 V.

c) U_a= 95,100,105 kV, U_g = 425 V.

In the last two cases the focusing electrode with R_{fe} =15 mm and r_{fe} = 3 mm was used. This shape of focusing electrode is better for practical realization to prevent discharges between electrodes.

Some interesting differences can be noted between these cases caused by the introduction of the grid. In the first case without the grid the changes of U_a are accompanied by corresponding variation of the current I_a so that the perveance remained practically constant and equal to P= 0.024μP. Phase space A of the beam changed only slightly so that the normalized emittance $\varepsilon = \gamma \beta A$ ($\gamma = m/m_0$, $\beta = v/c$) varied proportionally to changes of U_a. For all three values of U_a the focal distances and the dimensions of the emerging beam remained practically constant.

In the cases b) and c) the current intensity does not depend on U_a. The perveance only slightly decreases with increasing U_a and normalized emittance is again roughly proportional to U_a changing in the range (2.2÷2.64)$*\pi*10^{-6}$m*Rad.

A little more complicated are changes of the geometry of the emerging beam as a function of U_a. For U_g = 450 V and Ua = 95 kV most of the rays attain their minimal distance from the axis in the vicinity of $Z=Z_{min}$=(90-92) mm so that the emerging beam is slightly divergent. The radius of the waist is relatively large R_{min}= 0.5mm but the divergence is rather small being of the order of dR/dZ = 5mRad. The external ray is convergent having dR/dZ =-5.2mRad.

For U_a = 100kV the general features are similar but now almost half of the rays are convergent at the exit of the gun (Z = 96mm). The waist of the the beam at Z = (93-94)mm is smaller having

R_{min}= 0.34mm but the slope of some rays is larger : dR/dZ = (−10÷10)mRad. The external ray is still convergent with dR/dz = -9.9mRad.

For U_a = 105kV more than half of all rays are convergent at Z =96mm. The maximum radius at the exit is 0.28mm but the slope dR/dZ varies between (-10÷20)mRad, the most divergent being the external ray.

For U_g= 425V the situation at the exit is inversed. For U_a =95kV about half of the rays are still convergent at the end of the gun. The beam radius is there equal to R_{end} =0.32mm and the slope dR/dZ = ± 10mRad, the external ray is convergent.

There are no large changes for U_a = 100kV: the beam radius is a little smaller R_{end}= 0.3mm but dR/dZ for some of the rays (few starting in the vicinity of the axis and the external one) is about 20mRad. For U_a = 105kV all the rays are divergent at the exit forming the beam with R_{end} =0.54mm and dR/dZ=30mRad for the external ray.

It follows from these results that for a given value of U_a there exists an optimum value of U_g realizing the desired shape of the beam at the gun exit. The value of U_g is not critical, e.g. in the above considered gun for U_a = 100kV the optimum value of U_g is about 440÷450 V.

Another important result is rather good stability of the beam parameters against variations of the anode potential U_a. We have seen that few precent changes of U_a did not cause any change of the current intensity of the beam, the normalized emittance was roughly proportional to $\gamma\beta$ and the geometrical parameters of the beam at the distance of 100mm from the cathode remained acceptable: the radius of the beam was lower than 0.5mm and the slope of the most of the rays in the bunch was of the order of 10mRad.

This result can be useful when considering the stabilization of the power supply for the anode. Taking into account the the gun will be used for the injection system of LISA and knowing that the energy spread introduced during the process of phase bunching can be of the order of 10%, then the main requirement for the stability of the anode potential U_a will be the stability of the beam parameters at the output of the gun.

Above we have seen that from this point of view the stabilization of U_a below 1% would be good enough. Taking this into account we propose to accept 10^{-3} as required stability of U_a, simplifying thus the construction of power supply for the gun .

Below we summarize the parameters of the gun which we propose to accept for construction. (See Fig.1 for geometry):

Type	Pierce, triode
Current	I > 0.2A
Energy	W = 100kV
Energy dispersion	$\Delta W/W = 10^{-3}$
Emittance (invariant)	$\varepsilon < 5*\pi*10^{-6} m*Rad$
Cathode radius	R_k = 40mm
Grid radius	R_g = 39mm
Radius of focusing electrode	R_{fe} = 15mm
Curvature radius of focusing electrode	r_{fe} = 3mm
Length of focusing electrode	L_{fe} = 18mm
Anode radius	R_a = 2mm
Anode hole diameter	Φ_a = 8mm

The calculated parameters of this gun for U_a =100kV and U_g =445V are presented at Fig. 21 and in the Table II where the details concerning the electron trajectories are given. These data can be useful for the calculation of the parameters of the beam transport system.

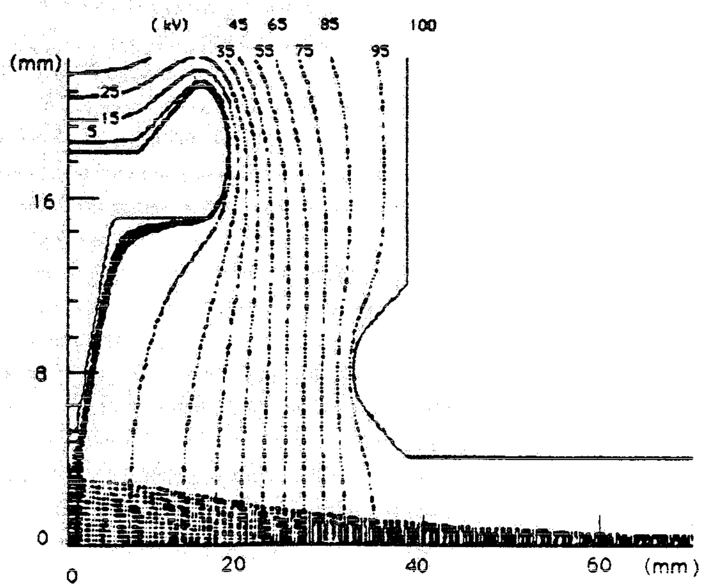

Fig 21 Electron trajectories and equipotential lines
for Ua =100kV , Ug = 445V
Beam current I= 0 7A, beam emittance ε =2 3 π 10-6 m* Rad

TABLE 11. Parameters of Electron Trajectories in the Gun.

U_a = 100 KV, U_g = 445 V, Current I = 0.7 A,

Normalized Emittance $\mathcal{E} = 2.8 * \pi \cdot 10^{-6}$ m*rad.

RAY	REND (MM)	ZEND (MM)	RMIN (MM)	RMAX (MM)	ZRMIN (MM)	ZRMAX (MM)	DR/DZ (MRAD)
1	0.05795	96.53130	0.0001	0.0654	53.1714	0.0000	3.16348
2	0.20063	96.53083	0.0003	0.1962	51.2514	0.0000	10.96833
3	0.20414	96.53098	0.0004	0.3270	59.5717	0.0000	11.58894
4	0.13178	96.53187	0.0008	0.4578	69.9722	0.0000	7.81638
5	0.06138	96.53291	0.0000	0.5886	80.6930	0.0000	4.50351
6	0.03086	96.53388	0.0003	0.7194	87.8939	0.0000	3.51333
7	0.00555	96.53509	0.0002	0.8503	95.0951	0.0000	3.29438
8	0.02569	96.53653	0.0269	0.9809	0.0000	0.0000	-2.56589
9	0.05331	96.53814	0.0542	1.1117	0.0000	0.0000	-1.82581
10	0.07337	96.53994	0.0741	1.2425	0.0000	0.0000	-1.51239
11	0.09577	96.54194	0.0963	1.3732	0.0000	0.0000	-1.07970
12	0.12127	96.54418	0.1214	1.5039	0.0000	0.0000	-0.40458
13	0.14301	96.54659	0.1424	1.6346	94.1466	0.0000	0.26188
14	0.15662	96.54916	0.1558	1.7653	93.9892	0.0000	0.36044
15	0.17603	96.55212	0.1740	1.8960	92.8721	0.0000	0.77073
16	0.19612	96.55521	0.1932	2.0266	92.5552	0.0000	1.07935
17	0.20185	96.55840	0.2010	2.1572	94.4784	0.0000	0.75295
18	0.19010	96.40228	0.1903	2.2878	0.0000	0.0000	-0.75924
19	0.23455	96.40632	0.2347	2.4184	0.0000	0.0000	-0.27467
20	0.28453	96.41064	0.2844	2.5489	95.7706	0.0000	0.28898
21	0.30324	96.41544	0.3033	2.6794	0.0000	0.0000	-0.24013
22	0.28701	96.41924	0.2875	2.8099	0.0000	0.0000	-1.59988
23	0.21481	96.42202	0.2162	2.9404	0.0000	0.0000	-4.15916
24	0.01100	96.42010	0.0148	3.0708	0.0000	0.0000	-11.80706

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