ISTITUTO NAZIONALE DI FISICA NUCLEARE

LNF (Laboratori Nazionali di Frascati)

INFN-20-10/LNF
4 August 2020

Electron Gun and Magnetic Systems Studies for a 36 GHz Klystron Amplifier

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Abstract

Self consistent analytic and numeric design for a set of innovative electron guns suitable for Ka-band klystrons is proposed in this paper. The proposed electron sources are designed to produces narrow beam with high currents that can be used in devices with critical dimensions. The proposed set of electron gun is destined to high power klystrons to be used as power sources for accelerating structures operating in Ka-Band. This family of accelerators is foreseen to achieve energy gradients around 150 MV/m. A klystron amplifier is being investigated in order to feed a linearizer structure. In this paper different electron gun and beam focusing channel designs are presented.

Published by
Laboratori Nazionali di Frascati

1 Introduction

The fundamental performance of all vacuum electron devices relie in the electron gun that, being the active device which produces the main electron stream to be manipulated, must respond to severe requirements and determines critically the feature of the power tube where it's applied to. In the proposed study, the self consistent analytic design and the numeric model for a set of innovative electron guns suitable for Ka Band klystrons is described. For Ka band klystrons, very small beam dimension are needed and the presented family of electron guns responds to this requirement. Thermionic filament have been used to indirectly heat the presented cathode and a high vacuum of about 10-7 Torr is required for the correct operation.

The proposed electron gun are developed as beam sources for the Ka-band klystrons under development for CompactLight XLS and also applyable to design a hard X-ray Free Electron Laser (FEL) facility using the latest concepts for bright electron photo injectors, very high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators [1]. The electron gun and the magnetic focusing system have to produce a 1mm beam radius confined in a 1.2 mm pipe radius in order to obtain about 26 MW beam power. Estimations have been obtained by using the numerical code CST [2] and analytical approaches. Also we are working on the design of the compact SW and TW accelerating structure operating on the third harmonic with a (100-125) MV/m accelerating gradient [3–5] . Moreover, this activity is also of strong concern for the local activity in the frame of Sparc-Lab project at INFN-LNF.

Space charge force is one of the limitation which doesn't allow to have identical velocity for each accelerated electrons after passing through the cavities by affecting the bunching process which leads to the low efficiency. The key element to control and measure such a force is known as perveance, $K = I\,V^{-3/2}$, where I and V stand for the beam current and voltage. We are planning to finalize the linearizer structure design and the RF power source that will be able to produce up to a 25 MW input power with an efficiency of about 50 $\%$. By considering that the efficiency is defined as the ratio of the output power to the input power, we conclude that the voltage is proportional to the ratio $(P_{out}/(\eta K))^{2/5}$. The higher the perveance, the stronger the space charge and consequently the weaker the bunching. On the other hand, since the perveance means how much current comes out of cathode for a certain voltage difference applied between the cathode and anode, to have a higher beam current we should rise the perveance, but higher perveance leads to low efficiency. As a results we have found an optimal perveance to maintain a good efficiency.

In this paper, we present different electron gun and magnetic focusing system designs in order to produce a 1mm beam radius confined in a 1.2 mm beam pipe to maximize the klystron efficiency. The klystron works on the third harmonic of the bunched electron beam ($\sim$35 GHz). The electron beam is generated from a high-voltage DC gun (up to 480 kV) and the cathode-anode geometry and the distance between them were optimized to adjust the electric field equipotential lines in order to obtain the extracted beam current of above 100 A.

In addition, the analytical approach for calculation of the electron gun's dimension has been accomplished and the results have compared with the numerical results through CST Particle Studio.

2 The main device limitations

In designing a high power klystron we have some limitations: a) beam current b) beam radius and c) cathode material. As we have mentioned before, in order to have a high beam current we should rise the perveance, but higher perveance leads to low efficiency and we have to find an optimal perveance to maintain a good efficiency. The beam radius r cannot be less than the Brillouin limit,

$$r_b = \frac{0.369}{B}\sqrt{\frac{I}{\beta\gamma}}\, mm \tag{1}$$

where, I is the beam current (I=100A), β denotes v/c for relativistic particle ($\beta = 0.860$), γ stands for the relativistic mass (energy) factor ($\gamma = 1.957$) and B is magnetic field in kG (B=32 kG). In our case, the Brillouin limit is 0.1312 mm. The beam radius should not be below this radius. Finally we investigated the limitation which is related to the cathode material used as the source of current emission. Tungsten filament and Lanthanum hexaboride (LaB_6) are two common materials used as source of current emission. LaB_6 has bigger lifetime than Tungsten. The other advantage of LaB_6 is that the emitted current is much bigger due to the low work function. We reported the properties of these material in Table 1.

Properties	Tungsten filament	LaB_6
Operating temperature [$^\circ K$]	2700-3000	1700-2100
Emitted current (J_c) [A/cm^2]	1.75	40-100
Required vacuum [Pa]	10^{-3}	10^{-4}
Average life time [hr]	60-100	600-1000
Work function [eV]	4.5	2.7

Table 1: Properties of cathode materials

We decided to work with LaB_6 as the cathode material in space charge limited regime in order to get a greater current emission and less cathode damage.

3 Electron Gun Injector Beam Dynamics Estimations

We have started the design of a Pierce-type electron gun as injector of the klystron operating at Ka-Band (35 GHz) in order to feed the accelerating structure. In this case, the cathode-anode voltage is about 480 kV, producing a beam current of about 100 A and beam power up to 48 MW. In Fig.(1), the preliminary simulation of the electron gun with CST is shown.

Beam trajectory (left) and electric field equipotential lines (right) are shown. The cathode-anode geometry was optimized to adjust the electric field equipotential lines in order to obtain a beam current extraction of 100 A. Design parameters of the diode gun for the Ka-band klystron are shown in Table 2.

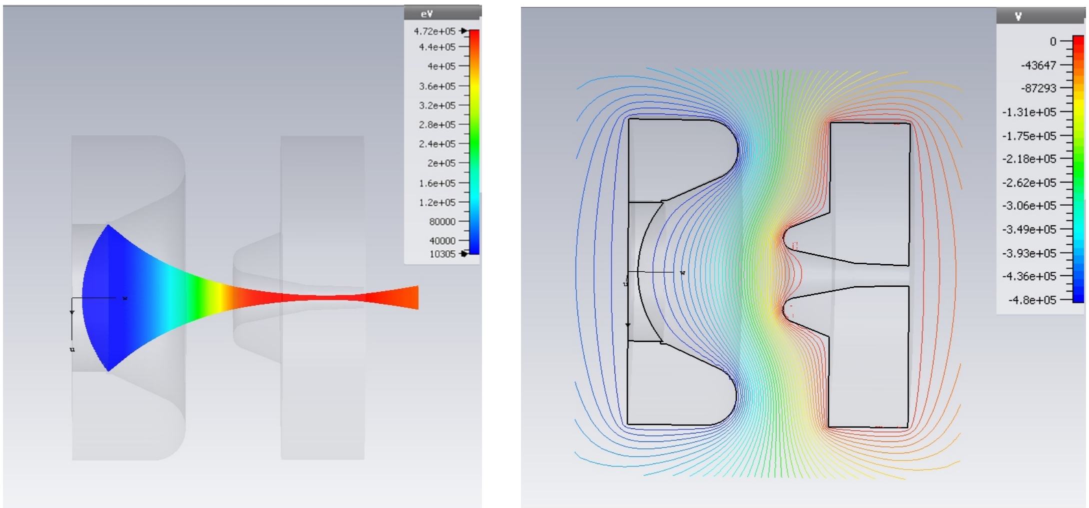
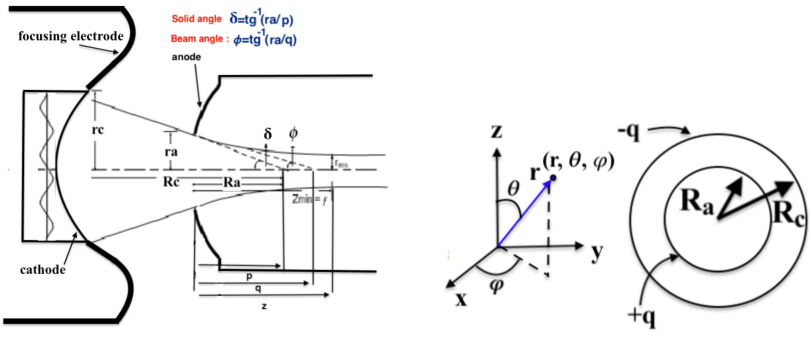


Figure 1: Preliminary electron gun design performed using CST Particle Studio. The cathode-anode voltage is 480 kV, producing a beam current of 100 A. Beam trajectory (left) and Equipotential lines (right) are shown.

Design parameters	
Beam power [MW]	48
Beam voltage [kV]	480
Beam current [A]	100
$\mu-$ perveance $[I/V^{3/2}]$	0.3
Cathode diameter [mm]	76
Max EF on focusing electrode [kV/cm]	200
Electrostatic compression ratio	1488

Table 2: Design parameters of diode gun for Ka-band klystron

We obtained the electrostatic beam compression ratio of 1488: 1. The μ perveance of the device is 0.3 $AV^{-3/2}$. It is common to use micro perveance because its order is typically of 10^{-6} $AV^{-3/2}$. Maximum electric field on focusing electrode is about 200 kV/cm which is a reasonable value. In order to avoid possible damage for a safety operation margin in terms of pulse length, the RF windows, power supply hardware stability, etc., we have decided to work with a 480 kV cathode-anode voltage.



(a) (b)

Figure 2: a) Schematic view of the Pierce-type gun geometry b) Two concentric conducting spheres of inner and outer radii R_a and R_c, equivalent with the DC gun

4 Analytical method for estimating the dimensions of electron gun device

An expression for the potential distribution between the cathode and anode may be obtained from considering Poisson's equation. Poisson's equation in spherical coordinates is,

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial V}{\partial r}) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}(\sin\theta\frac{\partial V}{\partial \theta}) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 V}{\partial \varphi^2} = -\frac{\rho}{\epsilon_0} \tag{2}$$

We have no variation of the potential in θ and ϕ coordinates because of the symmetry about the axes and the equation above becomes:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial V}{\partial r}) = -\frac{\rho}{\epsilon_0} = \frac{I}{4\pi r^2 \nu \epsilon_0} \tag{3}$$

where ν is the electron velocity. The above equation can be solved in terms of a series by H. M. Mott-Smith method. The final solution takes the form [6,7],

$$I = \frac{4\epsilon_0}{9}\sqrt{\frac{-2e}{m}}\frac{V^{3/2}}{(-\alpha)^2} \tag{4}$$

where m stands for the electron mass, α is a polynomial function of gamma; which is $\xi = log(\frac{R_a}{R_c})$ where R_a and R_c are the radii of the spheres where the anode and cathode respectively lie. (see Fig. 2) [8],

$$\alpha = \xi - 0.3\,\xi^2 + 0.075\,\xi^3 - 0.0143\,\xi^4 + ... \tag{5}$$

For klystrons in the space-charge limit, the beam current is proportional to the klystron voltage raised to the three-halves power. The constant of proportionality is known as the perveance.

The beam angle ϕ (see Fig.(2)) can be obtained from the electrostatic lens effect due to the anode aperture ($\phi = tg^{-1}(r_a/q)$) [9]. From analogy between light optics and charged-particle optics we have $\frac{1}{p} + \frac{1}{q} = \frac{1}{f} = \frac{E_2 - E_1}{4V_a}$ where $p = R_a$ and $E_2 = 0$ is the field on the anode. Then we have [9],

Parameters	Analytical	Numerical (CST)
$\frac{R_c}{R_a}$	3.18	3.125
r_a [mm]	11.64	13.10
Solid angle, δ	15.96°	18.13°
Beam angle, $\phi = tg^{-1}(r_a/q)$	13.11°	14.68°
Beam current [A]	100	100

Table 3: Comparison between analytical and numerical results for estimating the dimensions of electron gun device

$$\frac{1}{q} = \frac{1}{R_a} - \frac{E_1}{4V_a} \tag{6}$$

where E_1 is the field on the cathode side of the anode and V_a stands for the anode voltage. The comparison between analytical and numerical results for estimating the dimensions of electron gun device is presented in Table 3, where it can be observed that the analytical estimation of the solid angle, δ, is smaller comparing to numerical results and this results in a smaller anode radius. Numerical calculations for the other parameters such as beam angle and the ratio between cathode radius and anode radius are in agreement with the analytical ones.

5 Magnetostatic Simulation

As the beam propagates through the beam pipe after the electron gun exit, the transverse dimension begins to increase due to the intense space charge, especially for the high current beam of the order of hundreds of amperes. This is the reason why we have to use a transverse focusing magnet. To achieve the required compression of the beam after existing the electron gun, a magnetic field distribution has been used. The 3D model of the gun and beam pipe is shown in Fig (3a). In the larger beam pipe, we can arrange some slots in order to improve the vacuum pumping. In the buncher cavity and the output one have to be installed on the smaller beam pipe.The magnetic field profile is presented in the Fig. (3c) and the corresponding beam envelope is shown in Fig. (3b). We reported the design parameters of the gun with focusing magnetic field along the beam axis in Table 4.

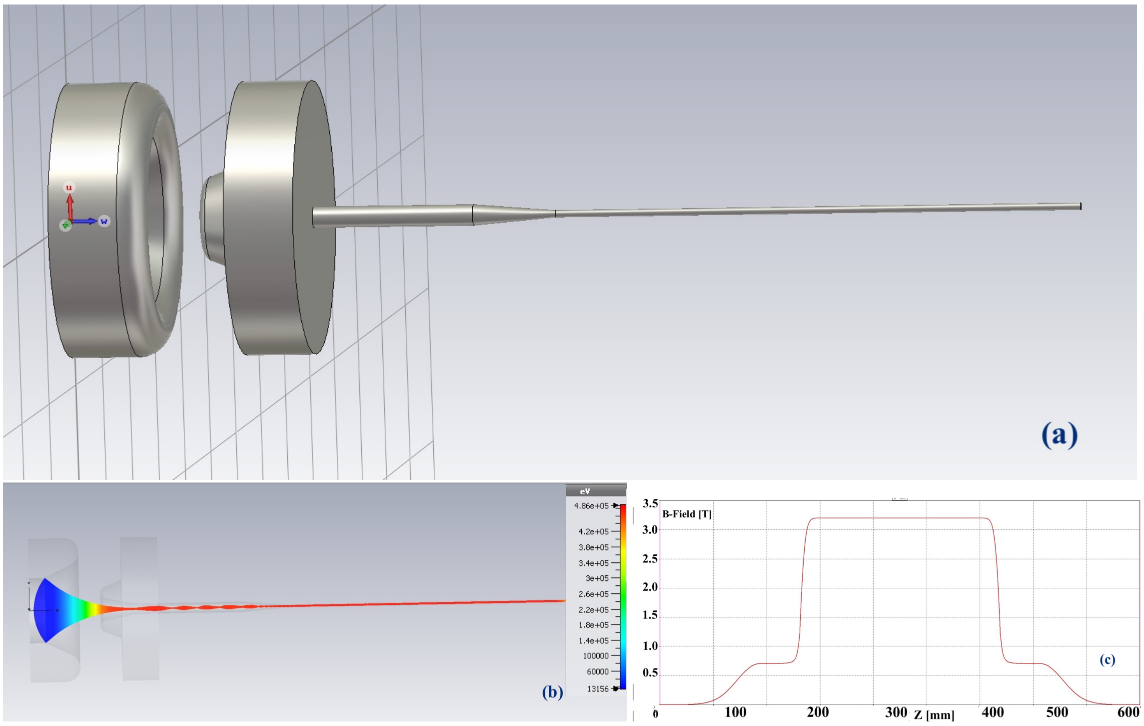


Figure 3: a) 3D model of the gun and beam pipe. The cathode-anode voltage is 480 kV, producing a beam current of 100 A b) Beam trajectory along the propagation direction c) axial magnetic field distribution.

Design parameters	
Beam power [MW]	48
Beam voltage [kV]	480
Beam current [A]	100
$\mu-$ perveance $[I/V^{3/2}]$	0.3
Cathode diameter [mm]	76
Pulse duration [μ sec]	0.2
Minimum beam radius in magnetic system [mm]	0.98
Nominal radius [mm]	1.00
Max EF on focusing electrode [kV/cm]	200
Electrostatic compression ratio	1488:1
Beam compression ratio	1635:1
Emission cathode current density $[A/cm^2]$	2.02
Transverse Emittance of the beam [mrad-cm]	1.23 π

Table 4: Design parameters of the gun with focusing magnetic field along the beam axis

As we observe from Fig. (3b), for the first rise and the last decay of the magnetic field profile we use the Rician distribution whose equation is as follows [10]:

$$f(z|\nu,\sigma) = \frac{z}{\sigma^2}\, e^{(\frac{-(z^2+\nu^2)}{2\sigma^2})}\, I_0(\frac{z\nu}{\sigma^2}) \tag{7}$$

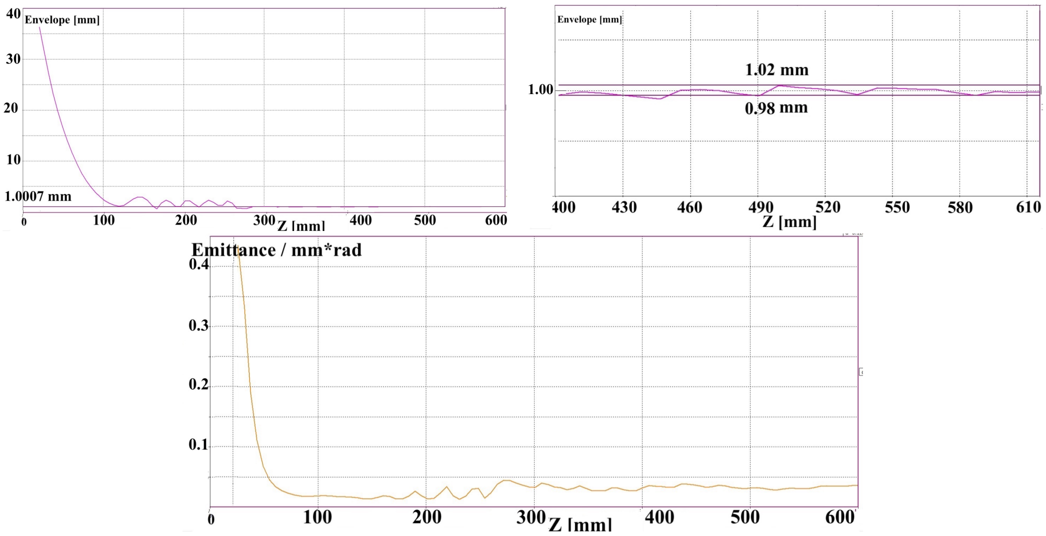


Figure 4: a) beam envelope and b) transverse emittance of the beam along the beam axis at the presence of the focusing magnetic field. The transverse emittance rises in the small beam pipe where we have the minimum beam radius. c) beam envelope inside the small pipe.

where $I_0(z)$ is the modified Bessel function of the first kind with order zero. The parameter ν is the position of the center of the peak, σ (the standard deviation) controls the width of the Rician distribution function and z is the height of the curve's peak. The reason we use this kind of distribution is that it is similar to the practical distribution used in the solenoids.

The magnetic field profile, Fig. (3b), has a small peak of 7 kG and a constant magnetic field of 32 kG along a distance of about 300 mm in order to have a narrow beam radius for the purpose of inserting the cavities operating on the third harmonic of the fundamental mode of X-band. These cavities are operated in Ka-Band and therefore they require a small beam radius of about 1 mm. The design parameters of the gun with focusing magnetic field along the beam axis are presented in Table 4. In the region before the small pipe, where we have mounted a tapered pipe, the magnetic field is 7 kG and consequently the beam radius is bigger $\sim$ 2.31 mm but this value is considerably higher than Brillouin limit in that region which is 0.6 mm. Likewise for the region where the field is 32 kG, the beam radius is $\sim$ 1 mm which again is much bigger than the Brillouin limit which is about 0.1312 mm.

In order to increase of the efficiency, we have to find an optimal perveance. As we have mentioned before, the efficiency and perveance are inversely proportional to each other [11] . This means, in order to obtain a high efficiency, the perveance should be small. The price we should pay is to have a small beam current. For this reason and also for other reason which we will report later in the next sections, we have decided to work with a beam current of 100 A. The corresponding μ-perveance is 0.3 $A/V^{3/2}$. It should be noted that with the μ-perveance is 0.657 $A/V^{3/2}$ which is a common perveance for designing a modern klystron, we could obtain 235 A, but with an efficiency much smaller the one we have obtained in the case that the beam has a current of 100A. To change the μ-perveance from 0.657 $A/V^{3/2}$ to 0.3 $A/V^{3/2}$, we have decided to not change the cathode-anode shapes which we could but we enlarged the distance between them, instead. As we observe from section 4, by enlarging the cathode-anode distance, the ratio $\xi = log(R_a/R_c)$ decreases. Then, α (see Eq. (5)) will be bigger and consequently the current obtained from Eg. (4) becomes smaller. The reason we have not changed the cathode radius in order to decrease the current is that because the electrostatic compression ratio becomes much smaller and also maximum electric field on focusing electrode has increased dramatically. Instead, by enlarging the cathode-anode distance, we have a higher electrostatic compression ratio, about 1488, and smaller electric field on focusing electrode which is about 20 MV/m. It should be noted that, the electrostatic compression ratio and maximum electric field on focusing electrode for the case of the μ-perveance of 0.657 $A/V^{3/2}$ are 210 and 24 MV/m.

To avoid of voltage breakdown and limitations of cathode loading, the maximum possible beam compression is necessary for designing the device [12]. In order to increase the beam compression one should take into account the transverse emittance; indeed, by increasing the beam compression, allowing the minimum beam radius, the transverse emittance rises as we can observe from Fig 4.

We have obtained the magnetostatic beam compression ratio of 1635:1 where the beam radius is $\sim$ 1 mm. It should be noted that it would be possible to rise the beam compression ratio to more than 2000:1 just by decreasing the beam radius to 0.9 mm. The maximum possible compression ratio is where the beam radius arrives to the Brillouin limit. The transverse emittances of the beam in the small pipe is 1.23 π (m rad-cm), respectively.

Design parameters	
Beam power [MW]	24
Beam voltage [kV]	480
Beam current [A]	50
$\mu-$ perveance $[I/V^{3/2}]$	0.15
Cathode diameter [mm]	45.5
Pulse duration [μ sec]	0.2
Minimum beam radius in magnetic system [mm]	0.82
Nominal radius [mm]	0.925
Max EF on focusing electrode [kV/cm]	210
Electrostatic compression ratio	106:1
Beam compression ratio	697:1
Emission cathode current density $[A/cm^2]$	2.67
Transverse Emittance of the beam [mrad-cm]	0.63 π

Table 5: Design parameters of the gun with focusing magnetic field along the beam axis

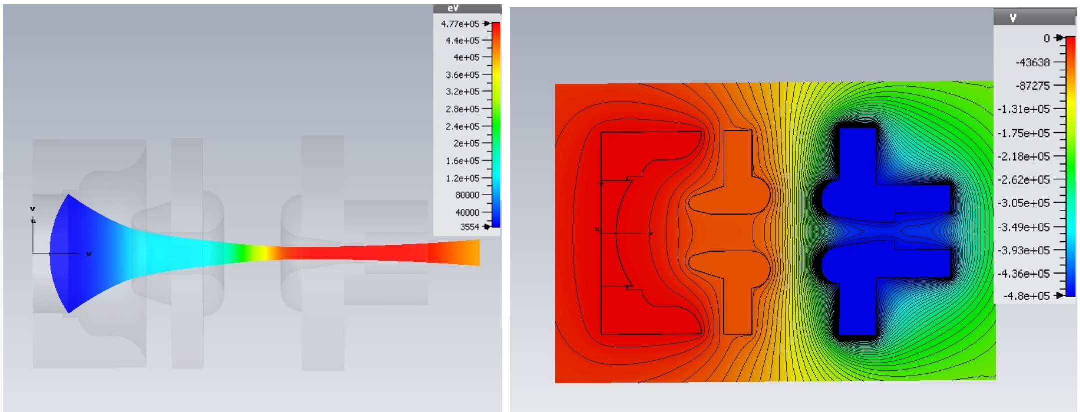


Figure 5: Preliminary two anodes electron gun design from CST. The cathode-anodes geometry was optimized to adjust the electric field equipotential lines in order to obtain a beam current extraction of 50A for the cathode-anode voltage of 480kV. Beam trajectory (left) and Equipotential lines (right) are shown.

Depending on the beam current required, for the new faminly of high power klystrons operating in Ka band that is being developed, two other electron gun can be useful. A very high current electron gun operating at 218A and a lower current electron gun operating at 50A are proposed. The design parameters of the gun with focusing magnetic field along the beam axis for the beam current of 50A are reported in Table. 5.

Beam trajectory (left) and electric field equipotential lines (right) are shown in Fig. (5). The cathode-anodes geometry was optimized to adjust the electric field equipotential lines in order to obtain a beam current extraction of 50A. Fig.s (6a), (6b) and (6c) show the 3D model of the gun and beam pipe, the beam trajectory along the propagation direction and the axial magnetic field distribution, respectively.

In order to investigate to see how we can manage to reduce the axial magnetic field distribution along the beam propagation, we use two anode configuration. The intermediate anode is being used for this purpose. Like the previous system with current electron gun operating at 100 A, the beam radius is 1 mm in a beam pipe of 1.2 mm. The magnetic field needed to compress the beam is reduced from 3.2 T to 0.7 T with this type of electron gun.

Design parameters of the gun with focusing magnetic field along the beam axis is reported in Table 6. The μ perveance of this device is 0.15 $AV^{-3/2}$ which is half of the one with 100 A. Maximum electric field on focusing electrode is about 210 kV/cm which is almost the same to the previous configuration with the standard one anode.

In Table. 6 we report the design parameters of the gun with focusing magnetic field along the beam axis for the current electron gun operating at 218 A . The design is the same as gun operating at 100 A but as we have mentioned in the previous section, the distance between cathode and anode is smaller and consequently the perveance is almost double.

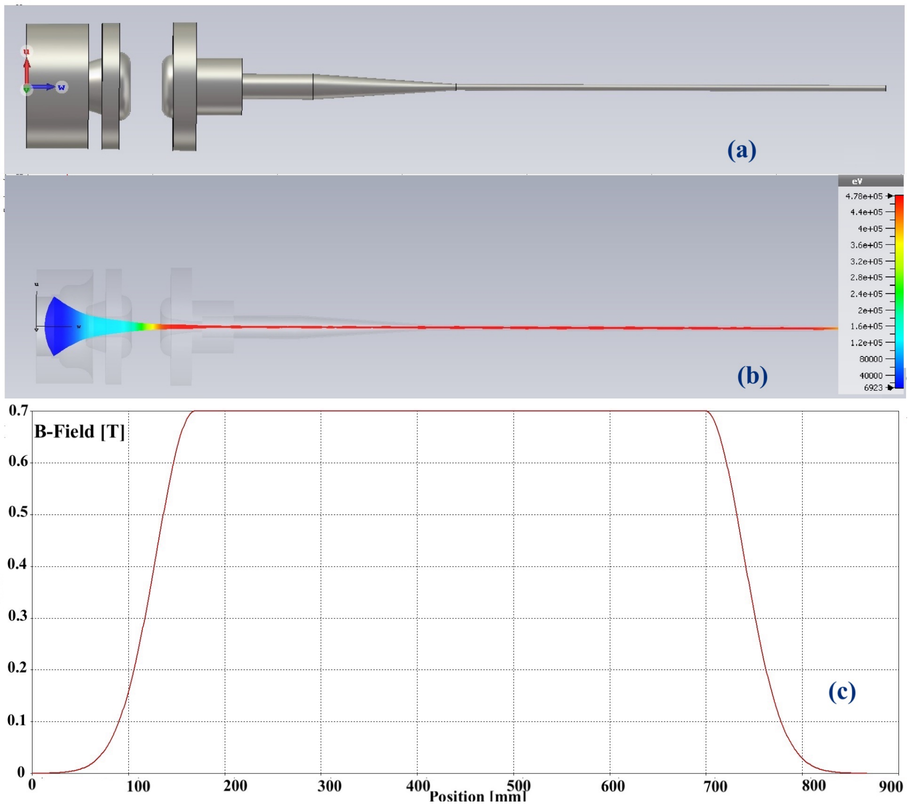


Figure 6: a) 3D model of the gun and beam pipe. The cathode-anode voltage is 480 kV, producing a beam current of 50 A b) Beam trajectory along the propagation direction c) axial magnetic field distribution.

Design parameters	
Beam power [MW]	105
Beam voltage [kV]	480
Beam current [A]	218
$\mu-$ perveance $[I/V^{3/2}]$	0.65
Cathode diameter [mm]	76
Pulse duration [μ sec]	0.2
Minimum beam radius in magnetic system [mm]	0.92
Nominal radius [mm]	0.99
Max EF on focusing electrode [kV/cm]	250
Electrostatic compression ratio	1488:1
Beam compression ratio	1635:1
Emission cathode current density $[A/cm^2]$	2.67
Transverse Emittance of the beam [mrad-cm]	0.63 π

Table 6: Design parameters of the gun with focusing magnetic field along the beam axis

6 Conclusions

In this paper, we estimated the dimensions of electron gun device analytically and the verification of theoretical analysis has been performed using CST code. Then, we accomplished the electromagnetic and beam dynamics design of an innovative electron guns suitable for Ka-band klystrons, by using the Microwave CST code. The electron flow is generated from a high-voltage DC gun (480 kV) and the different beam current (50A, 100A, and 218 A) have been extracted by changing the cathode-anode geometry in order to adjust the electric field equipotential lines. The electron beam is then transported through the klystron channel. The beam confinement is obtained by means of a high magnetic field produced superconducting coils. The channel has been optimized to deliver 24 MW, 48 MW and 105MW electron beams with a spot size of about 2mm diameter for 50A, 100A, and 218 A respectively.

In the forthcoming paper we will report the RF beam dynamics. In order to maximize the klystron efficiency we have decided to use the electron gun with the cathode voltage of 480kV and the beam current of 50A, 100A.

References

[1] http://www.compactlight.eu/Main/HomePage

[2] CST studio suite 2018. www.cst.com.

[3] M. Behtouei, L. Faillace, M. Ferrario, B. Spataro and A. Variola, "A possible RF Design on the 35 GHz accelerating structure for the Compact Light XLS project", Accepted for publication in Journal of Physics: Conference Series.

[4] Behtouei, Mostafa, et al. "New Analytical derivation of Group Velocity in TW accelerating structures."Journal of Physics: Conference Series. Vol. 1350. No. 1. IOP Publishing, 2019.

[5] Behtouei, Mostafa, et al. "A SW Ka-Band Linearizer Structure with Minimum Surface Electric Field for the Compact Light XLS Project."arXiv preprint arXiv:2003.02759 (2020).

[6] Langmuir, Irving. "The effect of space charge and residual gases on thermionic currents in high vacuum."Physical Review 2.6 (1913): 450.

[7] Blodgett, Katharine B. "Currents limited by space charge between concentric spheres."Thermionic Phenomena. Pergamon, 1961. 125-135.

[8] Pierce, J. R. "Rectilinear electron flow in beams."Journal of Applied Physics 11.8 (1940): 548-554.

[9] Haimson, J. “Some aspects of electron beam optics and X-ray production with the linear accelerator.”IRE Transactions on Nuclear Science 9.2 (1962): 32-49.

[10] Rice, Stephen O. “Mathematical analysis of random noise.”Bell System Technical Journal 23.3 (1944): 282-332.

[11] Chin, Y. H. “Design and performance of L-band and S-band multi beam klystrons.”Proceedings of LINAC08, Victoria, BC, Canada (2008): 363.

[12] Yakovlev, V. P., and O. A. Nezhevenko. “Limitations on area compression of beams from pierce guns.”AIP Conference Proceedings. Vol. 474. No. 1. American Institute of Physics, 1999.