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Initial electromagnetic and beam dynamics design of a Klystron amplifier for Ka-Band Accelerating Structures

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Abstract

In the framework of the Compact Light XLS project a compact third harmonic RF accelerating structure at 35.982 GHz with respect to the main Linac frequency 11.994 GHz, working with an ultra-high gradient accelerating field in order to linearize the longitudinal space phase is adopted. To this end an innovative high power Ka band klystron operating at about 35.982 GHz has to be designed for feeding the linearizer structure. In addition, we also are planning to design a Ka band klystron operating on the third harmonic of TM_{01} mode. The generation of a high density electron beam by using the Pierce type electron gun is also requested. The electron gun goal is to produce a converging high beam current that matches to a focusing magnetic field in such way to obtain about 100 MW beam power. This paper proposes a possible design of a electron gun to be used in millimetric waves vacuum tubes. We here report the preliminary studies of the electron gun and the related beam dynamic. Estimations have been obtained by using the numerical code CST and analytical approaches.

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1 Introduction

From all the way back of birth of the electronics, electron guns are the heart of electron devices. Vacuum tubes employ such electron source to produce the main electron current to be manipulated, in order to generate the output signals. In beam physics and radiation technology applications, electron guns are employed to produce a fundamental current of low energy electron. Such current can be injected in a linear accelerator to increase electron energy or can be directly used to generate ionizing radiation, by impacting on an ad-hoc target. The next generation of linear accelerators require unprecedented accelerating gradients for high energy physics and particle physics experiments. Technological advancements are strongly required to fulfill demands of compact linear accelerators for particle physics colliders, new accelerators devices from the compact or portable devices for radiotherapy to mobile cargo inspections and security, biology, energy and environmental applications and so on. The advantages of using high frequency accelerating structures are well known: smaller size, higher shunt impedance, higher breakdown threshold level and short filing time. Ultimately large electric gradients are also required for a variety of new applications, notably including the extreme high brightness electron sources for the FELs, RF photo-injector etc. Technological activities to design, manufacture and test new accelerating devices using different materials and methods are under way all over the world. In the framework of the Compact light XLS project, the main linac frequency is F=11.994GHz. In order to compensate the non-linearity distortions due to the RF curvature of the accelerating cavities, the use of a compact third harmonic accelerating structure working at F = 35.982 GHz is required [1–3]. Our concern is design a high power Ka band klystron in order to feed a constant impedance accelerating structure operating on the $2\pi/3$ mode with an average (100-125) MV/m accelerating electric field range by using the conservative main RF parameters. For this reasons we are planning to finalize the structure design as well as engineering of the RF power source that will be able to produce up to a 40-50 MW input power by using a SLED system [4,5] since the theoretical efficiency of the third harmonic Klystron operating on the TM_{01} mode is around the 18% (about a factor 3 less than the standard klystron efficiency). As a result, in order to obtain the RF power source requested, a 100 MW electron gun beam power is needed by knowing that the output cavity is operated in the third harmonic of the drive frequency in the TM_{01} mode. 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, $K = I\ V^{-3/2}$. 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 to find an optimal perveance to maintain a good efficiency. In this paper, a Ka-Band Klystron amplifer is being investigated in order to feed Ka-Band accelerating structures. The initial design is presented including the high-power DC gun and the beam focusing channel.

2 Electron Gun Injector Beam Dynamics Estimations

We have started the design of Pierce-type electron gun as a part of a klystron operating at Ka-Band (35 GHz) in order to feed the accelerating structure. In this case, the cathode-anode voltage is about 500 kV, producing a beam current of about 200 A and beam power up to 100 MW. In Fig. 1, the preliminary simulation of the electron gun with CST is shown. Beam trajectory (left) and electric field equipotential lines (right) have been

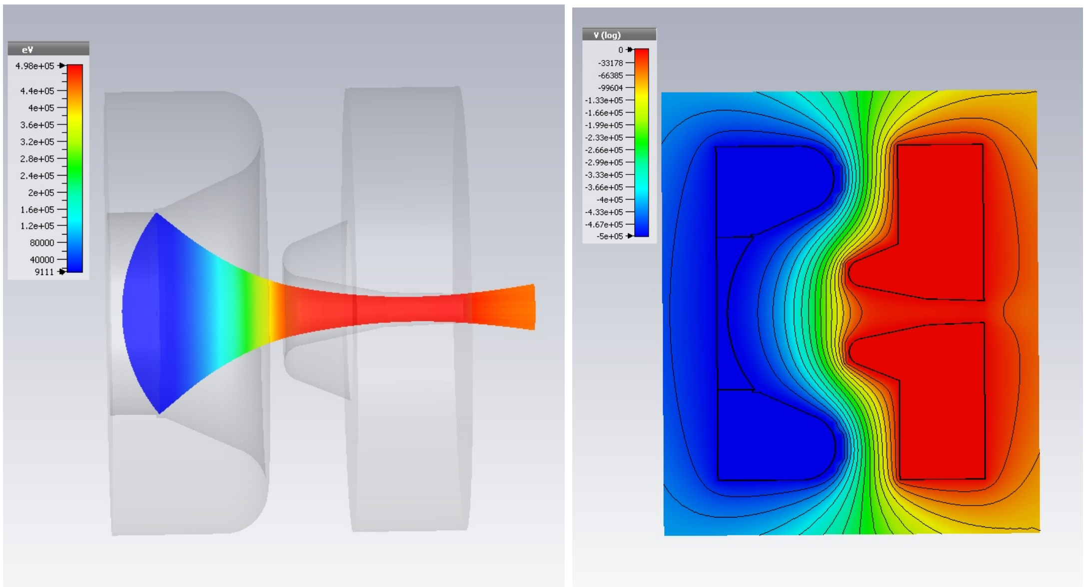


Figure 1: Preliminary electron gun design from CST. Beam trajectory (left) and Equipotential lines (right) are shown.

shown. The cathode-anode geometry was optimized to adjust the electric field equipotential lines in order to obtain maximum beam current extraction and capture (above 200 A). Design parameters of diode gun for Ka-band klystron have shown in Table 1.

Table 1: Design parameters of diode gun for Ka-band klystron

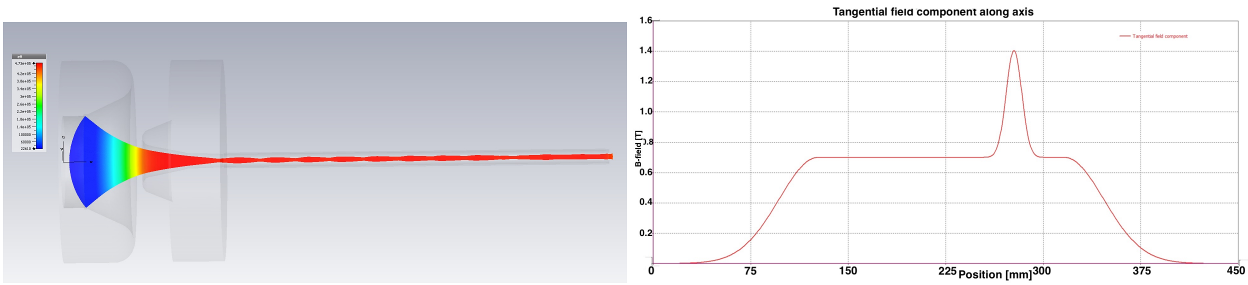
Beam power [MW]	118
Beam voltage [kV]	500
Beam current [A]	238
$\mu-$ perveance $[I/V^{3/2}]$	0.67
Cathode diameter [mm]	76
Max EF on focusing electrode [kV/cm]	240
Electrostatic compression ratio	210

We obtained the electrostatic beam compression ratio of 210: 1. To rise the compression ratio we have to apply focusing magnetic field and it will be reported in the next section. The μ perveance of the device is 0.67 $AV^{-3/2}$. 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 240 kV/cm which is a reasonable value. In order to avoid possible damage for a safety operation margin in terms of pulse length, windows, power supply hardware stability, etc., we have decided to work with a 480 kV cathode-anode voltage with maximum electric field of $\sim$ 200 kV/cm on focusing electrode as it will be reported in the next section.

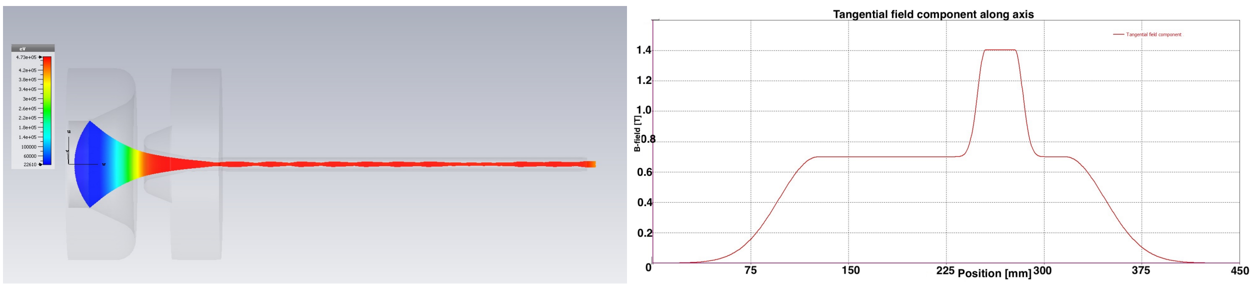
3 Magnetostatic Simulation

As the beam propagates through the beam pipe after the electron gun exit, the transverse dimension growth of the beam begin to increase due to the intense space charge, especially at the high current beam of several hundreds of amperes. This is the reason why we have to use transverse focusing magnet. Modern klystrons use electromagnet solenoids and the old ones used permanent magnet focusing. To achieve the required compression of the beam after existing the electron gun, a solenoid with two different distribution has been used. Two different field profiles are presented in the Fig. 2 (right) and corresponding beam envelope are shown (left).

Magnetostatic Simulation by CST Particle Studio



Model 1



Model 2

Figure 2: Beam trajectory along the propagation direction (left) and Axial magnetic field distribution (right) for two different models. Model 1 has a small peak of 14 KG model 2 has the same amplitude but a constant magnetic field about 30 mm at that manitude.

Model 1 shows the magnetic field profile with a plateau value of 7 kG, with a peak of 14 kG, and model 2 has the same amplitude but a constant magnetic field of 14 KG along a distance of 30 mm in order to have a narrow beam radius for the purpose of putting the output cavities which should be operated at Ka band and it requires a small beam radius of about 2 mm in order to achieve the beam radius as small as possible. The gun parameters are presented in Table 2.

Table 2: Design parameters of the gun with focusing magnetic field along the beam axis

Design parameters	Model 1	Model 2
Beam power [MW]	104	104
Beam voltage [kV]	480	480
Beam current [A]	218	218
$\mu-$ perveance $[I/V^{3/2}]$	0.657	0.657
Cathode diameter [mm]	76	76
Pulse duration [μ sec]	1	1
Beam radius in magnetic system [mm]	1.04	1.09
Max EF on focusing electrode [kV/cm]	208	208
Electrostatic compression ratio	210:1	210:1
Beam compression ratio	1635:1	1489:1
Emission cathode current density [kV/cm]	3.92	3.92
Transverse Emittance of the beam [m rad-cm]	1.39 π	1.41 π
Beam energy density [kJ/cm^2]	5.37	5.37

In the region, where magnetic field is of 7 kG, the beam radius is $\sim$ 2.2 mm considerably higher than Brillouin limit which is 0.6 mm and likewise for the region, where the field is of 14 kG, the beam radius is $\sim$ 1 mm which again is much bigger than the Brillouin limit which is about 0.3 mm.

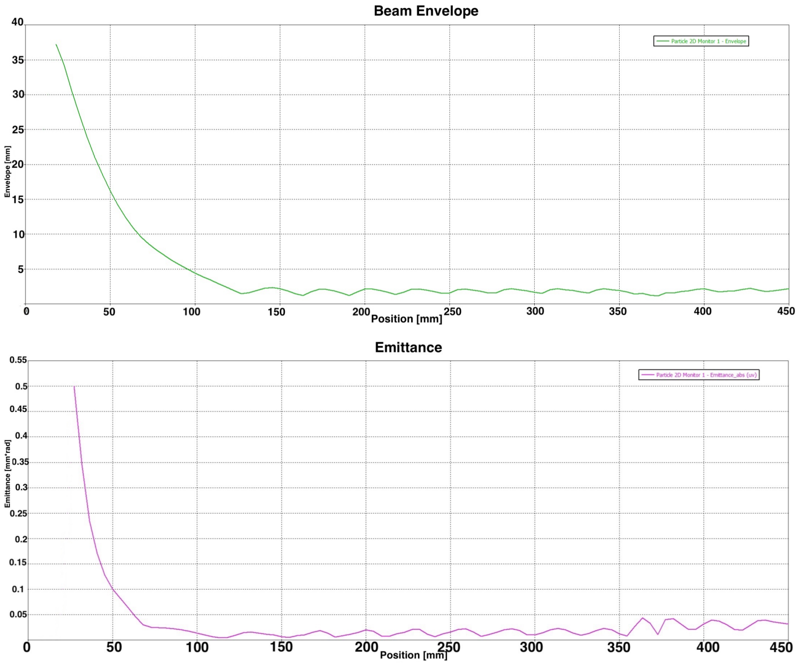
As it can be observed from Fig. 2, for the first rising and the last declivity of the magnetic field profile we use the Rician distribution which the equation is as follows [6]:

$$f(z|\nu,\sigma) = \frac{z}{\sigma}\, e^{\left(\frac{-(z^2+\nu^2)}{2\sigma^2}\right)}\, I_0\left(\frac{z\nu}{\sigma^2}\right) \tag{1}$$

where $I_0(z)$ is the modified Bessel function of the first kind with order zero. The reason we use this kind of distribution is that, it is similar to the practical distribution uses in the solenoids.

As the perveance means how much current comes out of cathode for a certain voltage difference applied between the cathode and anode, to have a high beam current we should rise the perveance, but higher perveance leads to low efficiency [7] and we have to find an optimal perveance to maintain a good efficiency. In our case the μ-perveance is 0.657 $A/V^{3/2}$ which is a common perveance for designing a modern klystron.

To avoid of voltage breakdown and limitations of cathode loading, the maximum possible beam compression is necessary for designing the device [8]. To increase the beam compression one should take into account the transverse emittance because increasing the beam compression for having the minimum beam radius, transverse emittance rises as we can observe from Fig 3.



(a)

(b)

Figure 3: a) beam envelope and b) transverse emittance of the beam along the beam axis at the presence of the focusing magnetic field

We have obtained the magnetostatic beam compression ratio of 1635:1 for the model 1 where the beam radius is $\sim$ 1 mm. It should be noted that it would be possible to rise the beam compression ratio more than 2000:1 just by decreasing the beam radius to 0.9 mm. The maximum possible compression ratio is 4914 where the beam radius arrives to the Brillouin limit of 0.6 mm. The problem of higher compression ratio, as we have mentioned before, which results in transverse emittance growth of the beam where the walls intercept the beam. The transverse emittance of the beam for the model 1 and 2 are 1.39 π (m rad-cm) and 1.41 π (m rad-cm), respectively.

4 The main device limitations

In designing a high power klystron we have some limitations: a) beam current limitation b) beam radius limitation and c) cathode material limitation. As the perveance means how much current comes out of cathode for a certain voltage difference applied between the cathode and anode, 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,

$$r_b = \frac{0.369}{B} \sqrt{\frac{I}{\beta\gamma}}\, mm \tag{2}$$

where,
I: Current beam (I=235A)
β: v/c for relativistic particle ($\beta = 0.860$)
γ: Relativistic mass (energy) factor ($\gamma = 1.957$)
B: Magnetic field in kG (B=14 kG)

and finally we investigated the later limitation which is the common materials used as a source of current emission. Tungsten filament and Lanthanum hexaboride (LaB6) are two common materials used as source of current emission. LaB6 has bigger lifetime than Tungsten. The other advantage of LaB6 is that, emitted current is much bigger due to the low work function. We reported the properties of these material in Table 3.

Table 3: Properties of cathode materials

Properties	Tungsten filament	Lanthanum hexaboride (LaB6)
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	longer than Tungsten
Work function [ev]	4.5	2.7

We decided to work with LaB6 as a cathode material in space charge regime limited in order to get a greater current emission and less cathode damage.

5 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,

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial V}{\partial r}) + \frac{1}{r^2 sin\theta}\frac{\partial}{\partial\theta}(sin\theta\frac{\partial V}{\partial\theta}) + \frac{1}{r^2 sin^2\theta}\frac{\partial^2 V}{\partial\phi^2} = -\frac{\rho}{\epsilon_0} \tag{3}$$

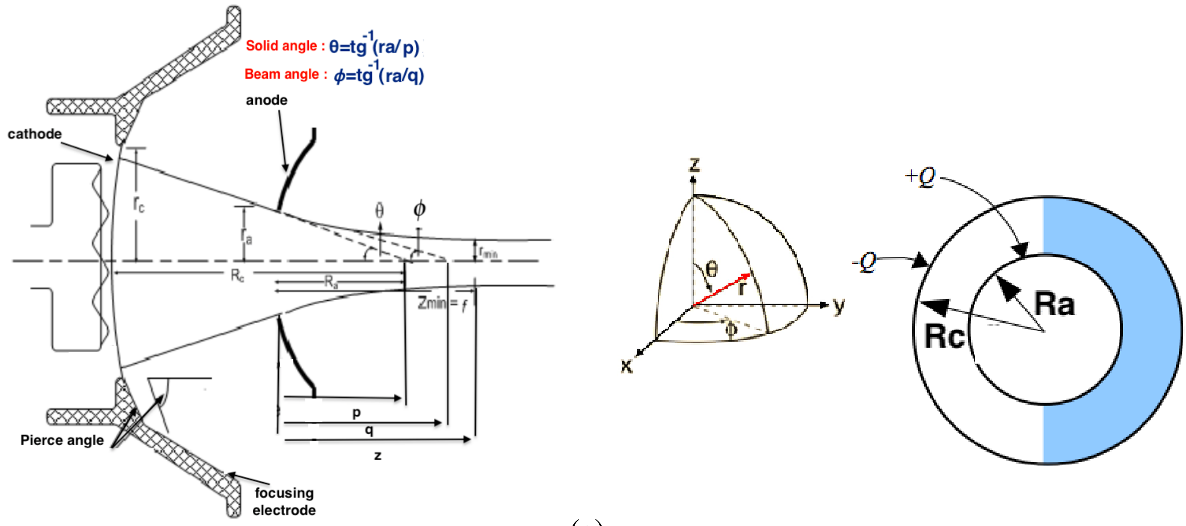
We have no variation of the potential in θ and ϕ coordinates because of the symmetry about the axes and the equation above becomes:

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

The above equation can be solved in terms of a series by H. M. Mott-Smith method [9]. The final solution takes the form [10],

$$I = \frac{16\pi\epsilon_0}{9}\sqrt{\frac{-2e}{m}}\frac{V^{3/2}}{(-\alpha)^2} = \frac{16\pi\epsilon_0}{9}\sqrt{\frac{-2e}{m}}V^{3/2}(\frac{r_c}{r_a})^2 \tag{5}$$

where α is a function of the ratio of the radii r_a and r_c of the spheres, r_c being the radius of the emitter and r_a is the anode radius (see Fig. 4), $\gamma = log(\frac{r_a}{r_c})$



(a) (b)

Figure 4: a) Schematic view of the Pierce-type gun geometry [11] b) Two concentric conducting spheres of inner and outer radii R_a and R_c, equivalent with the DC gun

$$\alpha = \gamma - 0.3\gamma^2 + 0.075\gamma^3 - 0.0143 + ... \quad (6)$$

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. Since the perveance of a typical klystron is on the order of 1×10^{-6}, a more common unit is the microperveance.

Table 4: Comparison between Analytical and numerical results for estimating the dimensions of electron gun device

Parameters	Analytical	Numerical (CST Particle Studio)
$\frac{r_c}{r_a}$	2.67	3.78
r_a [mm]	13.85	9.79
Solid angle, θ	34.72°	26.08°
Beam angle, $\phi = tg^{-1}(r_a/q)$	28.04°	18.07°
Beam current [A]	228	238

The beam angle ϕ (see Fig. 3a) can be obtained from electrostatic lens effect due to the anode aperture ($\phi = tg^{-1}(r_a/q)$) [12],

$$\frac{1}{q} = \frac{1}{R_a} - \frac{E}{4V_a} \quad (7)$$

where E is the field on the cathode side of the anode. Comparison between Analytical and numerical results for estimating the dimensions of electron gun device is presented in Table 4. As we observe from the table, we obtained emitted current of 238 A and 228 A from the cathode by numerical and analytical methods, respectively, which are in a good agreement. Analytical estimation of solid angle, θ, is larger comparing to numerical results and this results a bigger anode radius as we observe from the Table 4. 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.

Conclusions

In this paper, we have performed the initial electromagnetic and beam dynamics design of an RF Klystron amplifier in order to feed Ka-Band accelerating structures, by using the Microwave CST code. The klystron works on the third harmonic of the bunched electron beam ($\sim$35 GHz). The electron flow is generated from a high-voltage DC gun (up to 500 kV) and the cathode-anode geometry was optimized to adjust the electric field equipotential lines in order to obtain maximum beam current extraction and capture (above 200 A). The electron beam is then transported through the klystron channel. The beam confinement is obtained by means of a high magnetic field produced by superconducting coils, in the current design , which was analytically imported into the code. The channel optimization allows to deliver a 100 MW electron beam with a spot size below 2mm diameter. We are currently working on the 2D beam dynamics design of the input, bunching and output RF cavities of this klystron and further details will be given in a following paper. A tapered tunnel is expected to be installed in order to allocate Ka-band output cavities. We are also considering the possibility of using normal conducting coils instead of superconducting ones.

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