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

M. Behtouei, L. Faillace, M. Ferrario, B. Spataro and A. Variola

INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy

Abstract

High-gradient high-frequency accelerating structures are in strong demand for the next generation of compact light sources. Accelerating structures operating in Ka-Band are foreseen to achieve gradients around 150 MV/m. Among possible applications of a Ka-Band accelerating structure we refer to the beam phase-space manipulation for the Compact Light XLS project as well and medical and industrial applications. In this paper, a Ka-Band Klystron amplifier 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.

Introduction

- An innovative RF power supply at ∼35GHz was demonstrated more than a decade ago, the magnicon [1] which produced a peak output RF power of 17 MW with a gain of 47 dB at a pulse length up to 1.5 μs and a repetition rate up to 5 Hz.
- We have recently started a research activity on the re-design of the old magnicon in order to improve the output power and the repetition rate at least up to 100 Hz [2].
- The research project is devoted to the R&D of key components for existing accelerators and for the next generation of accelerators.
- New technologies are necessary to achieve the multi-TeV energies of future linear colliders, x-ray FELs, etc.

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,

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

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 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.

Electron Gun Injector Beam Dynamics

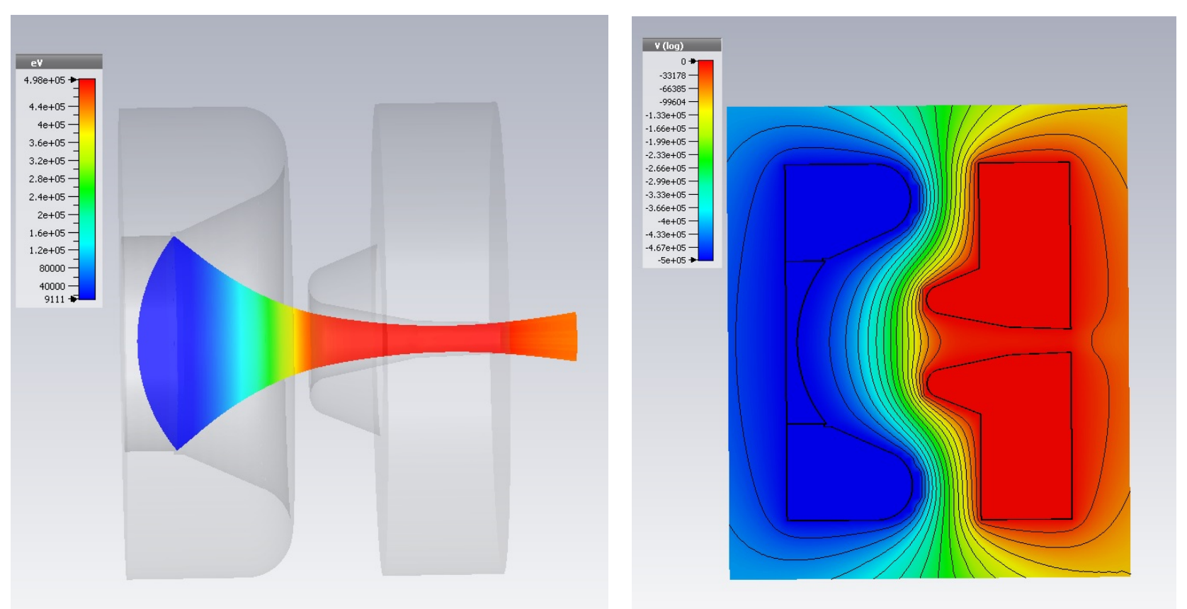


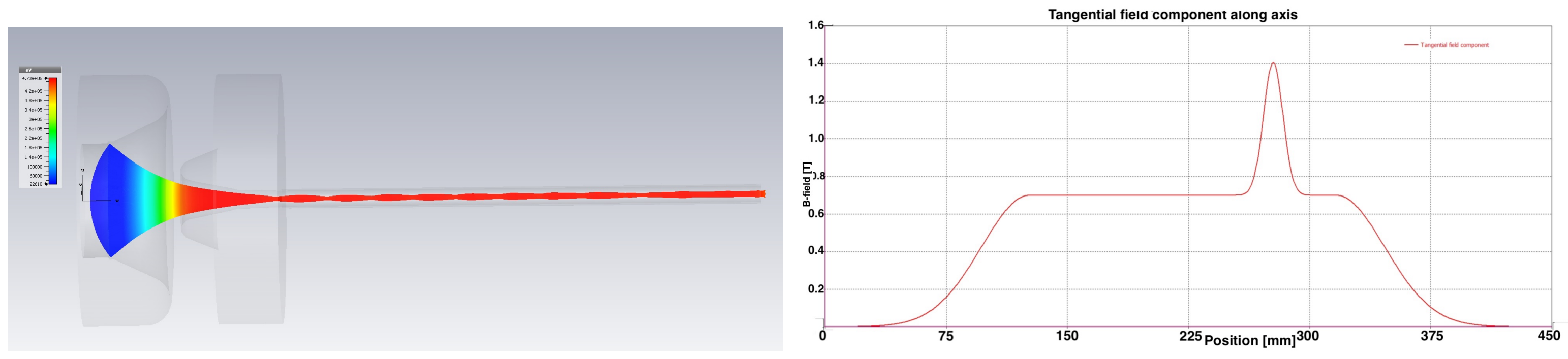
Fig. 1: Preliminary electron gun design from CST. Beam trajectory (left) and Equipotential lines (right) are shown..

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

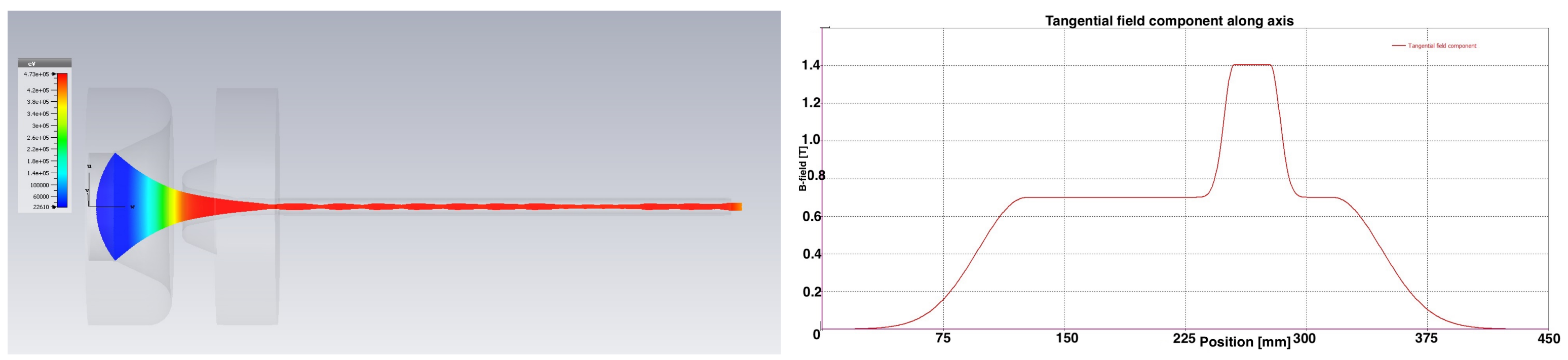
Table 1: Design parameters of diode gun for Ka-band klystron

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 240 A and beam power up to 118 MW. In Fig. 1, the preliminary simulation of the electron gun with CST is shown. Design parameters of diode gun for Ka-band klystron have shown in Table 1.

Magnetostatic Simulation



Model 1

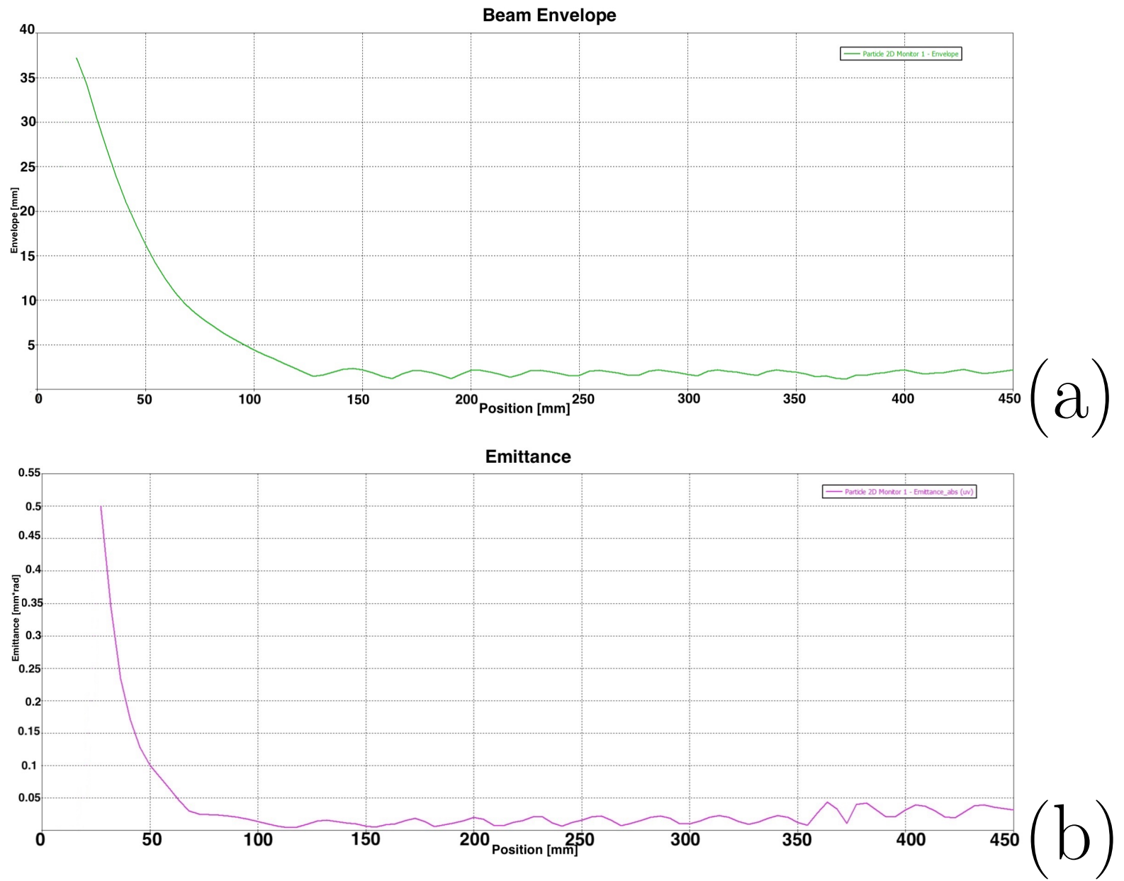


Model 2

Fig. 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 and model 2 has the same amplitude but a constant magnetic field about 30 mm at that manitude.

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 have shown (left). Model 1 has a small 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 which forcing us to get the beam radius as small as possible. The gun parameters are presented in Table 2. In the region, where magnetic field is of 7 kG, the beam radius is ∼ 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 ∼ 1 mm which again is much bigger than the Brillouin limit which is about 0.3 mm.

beam envelope and transverse emittance of the beam



(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

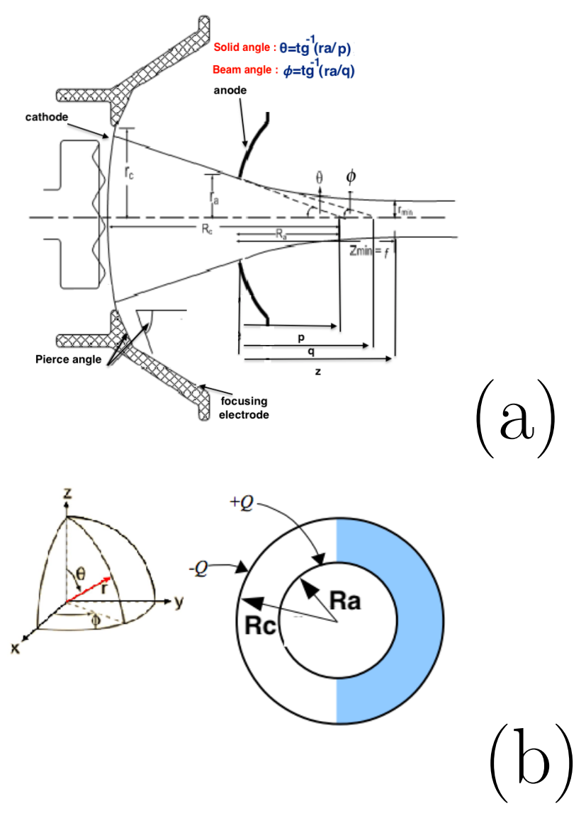
To avoid of voltage breakdown and limitations of cathode loading, the maximum possible beam compression is necessary for designing the device [3]. To increase the beam compression one should take into account the transverse emittance because increasing the beam compression for having the minimum beam radius, transverse emittance rises as we can observe from Fig 3. We have obtained the magnetostatic beam compression ratio of 1635:1 for the model 1 where the beam radius is ∼ 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 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.

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

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

Analytical method for estimating the dimensions of electron gun device



(a)

(b)

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

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,

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

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

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

The above equation can be solved in terms of a series by H. M. Mott-Smith method [5]. The final solution takes the form [6],

$$I = \frac{16\pi\epsilon_0}{9}\sqrt{\frac{-2e}{m}}\frac{V^{3/2}}{(-\alpha)^2} = \frac{16\pi\epsilon_0}{9}\sqrt{\frac{-2e}{m}}V^{3/2}(\frac{r_c}{r_a})^2 \tag{4}$$

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), $\gamma = log(\frac{r_a}{r_c})$

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

Comparison between analytical and numerical results

Parameters	Analytical	Numerical (CST)
$\frac{r_c}{r_a}$	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

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

The beam angle ϕ (see Fig. 4a) can be obtained from electrostatic lens effect due to the anode aperture ($\phi = tg^{-1}(r_a/q)$) [7],

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

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 3. 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. Numerical calculations for the other parameters such as solid angle, beam angle and the ratio between cathode radius and anode radius are in agreement with the analytical ones.

Conclusions

- 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 (∼35 GHz) [2].
- 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 eletric field equipotential lines in order to obtain maximum beam current extraction and capture (above 200 A).
- The electron beam is then transnported 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. We are also considering the possibility of using normal conducting coils instead of superconducting ones.

References

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