Design studies on the High Power Electron Gun for the Klystron operating at F= 35.982 GHz

presented by

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on behalf of SPARC-Lab (INFN-LNF)

in the framework of the Compact Light XLS project collaboration

Activity summary

100 MW electron gun design studies

Solenoid design analytical for beam focusing

Main components of the klystron

The basic components of a klystron device

- **Electron Gun**
- **Drive Cavity**
- **Bunching Cavities**
- **Output Cavities**
- **Solenoid Focusing Magnets**

The goal is to design a 36 GHz Klystron

In this presentation we show the electron gun preliminary studies

The main device limitation of the Klystron

1. Beam current limitation (perveance: higher value of the perveance leads to the device low efficiency

2. Beam radius can not be less than the Brillouin limit one

3. Cathode material limitation (current and lifetime)

Perveance and klystron efficiency

The perveance indicates how much beam current comes out from the cathode when the voltage V is applied between the cathode and the anode

$$p = I / V^{3/2}$$

usual values are of the order (0.6-0.7) $\times 10^{-6}$

Theoretical efficiency of standard klystron operating on TM_{01} $\Leftarrow\Rightarrow$ $\eta_1 = 0.58$ [2]

Theoretical efficiency of the third harmonic of TM_{01} $\Leftarrow\Rightarrow$ $\eta_3 = 0.18\ \eta_1$ (2)

In general by increasing the perveance, the efficiency decreases [3]

[2] G. Caryotakis - Stanford Linear Accelerator Center, SLAC-PUB, 2004 and INFN-LNF, SPARC-LAB group;
[3] Y. H. Chin, Proceedings of LINAC08, TU204, Victoria, BC, Canada.

Brillouin limit estimation

The beam radius r can not be less than the Brillouin limit, r_b

$$r_b = 0.369/B\,(I/\beta\gamma)^{0.5} \quad \text{(mm)}$$

I : Current beam (A)

β : v/c for relativistic particle

γ : Relativistic mass (energy) factor

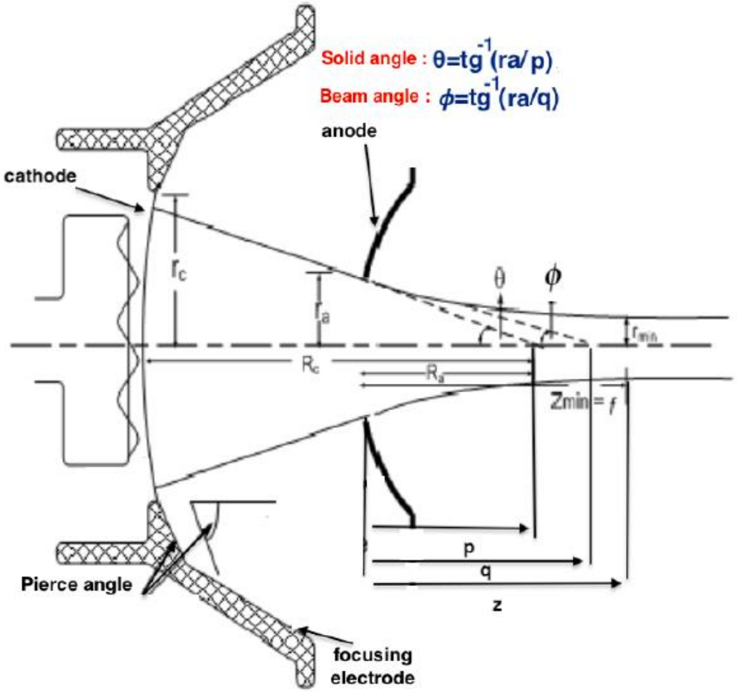
B : Magnetic field (kG)

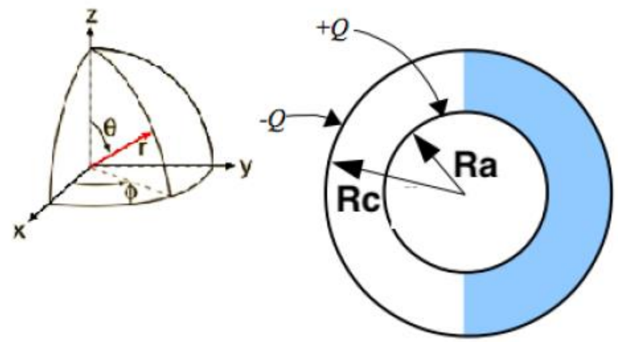
As an example, by assuming I =235 A, β = 0.860, γ = 1.957, B = 14 kG the beam radius is about

$$r_b \sim 0.3 \text{ mm}$$

This value matches with the 36 GHz cavity since the iris radius of this cavity is 1.333 mm as I already discussed in Trieste or Barcelona

Basic scheme of the electron gun with two electrodes





Two concentric conducting spheres of inner and outer radii R_a and R_c

Numerical simulations have been carried out by using the CST software

In addition, a check of these results has been done with analytical approaches

An expression for the **potential distribution** between t
cathode and anode may be obtained from considering
Poisson's equation:

$$\nabla^2 \mathbf{V} = -\frac{\rho}{\varepsilon_0}$$

electrostatic lens method

Analytical method for estimating the dimensions of electron gun device

Poisson's equation in spherical coordinates

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial V}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 V}{\partial\phi^2} = -\frac{\rho}{\varepsilon_0}$$

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

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V}{\partial r}\right) = -\frac{\rho}{\varepsilon_0} = \frac{I}{4\pi r^2 v\varepsilon_0}$$

$$I = \frac{16\pi\varepsilon_0}{9}\sqrt{\frac{-2e}{m}}\frac{V^{3/2}}{(-\alpha)^2} = \frac{16\pi\varepsilon_0}{9}\sqrt{\frac{-2e}{m}}V^{3/2}\left(\frac{r_c}{r_a}\right)^2$$

r_c = emitter radius

r_a = anode aperture radius

The proportionality constant is the perveance

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

$$\alpha = \gamma - 0.3\gamma^2 + 0.075\gamma^3 - 0.0143 + \ldots.$$

Electrostatic lens estimations (1965 J. H.)

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

$$1/q = 1/R_a - E/4V_a$$

V=500 kV, E=24 MV/m and Ra = 20 mm, q would be: 26 mm. Finally the beam angle would be: $\phi = 28.04^\circ$

It is one of the best cathode voltage candidate (V=500 kV) for 36 GHz structure.

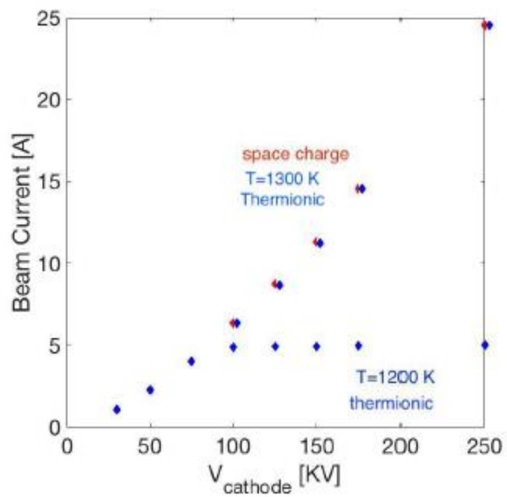
Cathode operation

Thermionic limit (Richardson's equation) → $I_A = AT^2 exp(-\frac{W}{kT})$

Where A,T,W and K are Richardson constant, operating temperature, matertial work functio and Boltzman, respectively

Space-charge limit (Langmuir's equation[1]) → $I = \frac{16\pi\varepsilon_0}{9}\sqrt{\frac{-2e}{m}}\frac{V^{3/2}}{(-\alpha)^2}$

The constant of proportionality in the space charge limit is known as the perveance.



Cathode material

Common materials used as a source of current emission:

- Tungsten filament cathode
  - Operating temperature 2700-3000 K
  - Emitted current $J_c = 1.75 A/cm^2$
  - Required vacuum 10^{-3}Pa
  - Average life time of 60-100 hours
  - Work function 4.5 eV
- Cathode in Lanthanum hexaboride (LaB6)
  - Operating temperature 1700-2100 K
  - Emitted current $J_c = (40 - 100) A/cm^2$
  - Required vacuum 10^{-4}Pa
  - Lifetime is longer than Tungsten filament cathode
  - Work function 2.7 eV

*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.

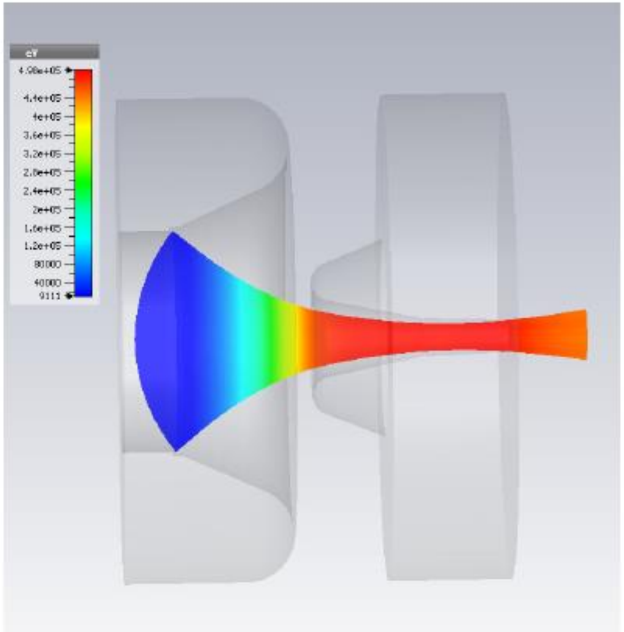
High Power Electron gun simulation by CST Particle Studio

High Power Electron Gun Simulation (based on ref. [8])

Beam energy

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

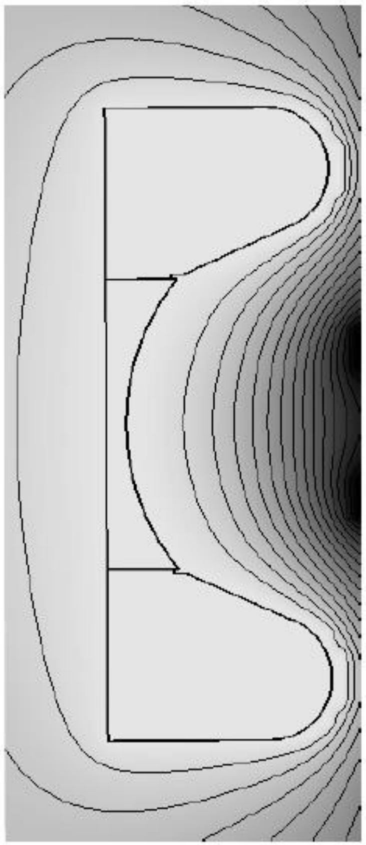


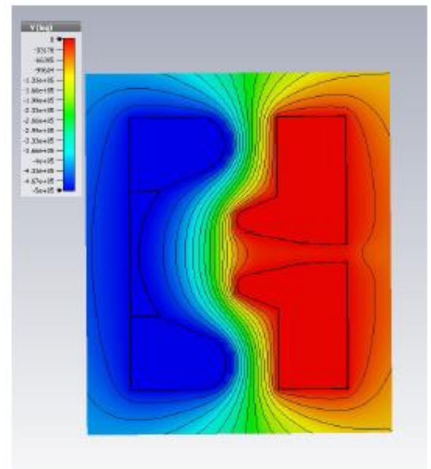
Analytical estimation of the beam current and beam optic behaviour are in good agreement with the CST ones

[8] Y.V. Baryshev, et al., A 100 MW electron source with extremely high beam area compression, NIMA340 (1994) 241-258 North-Holland.

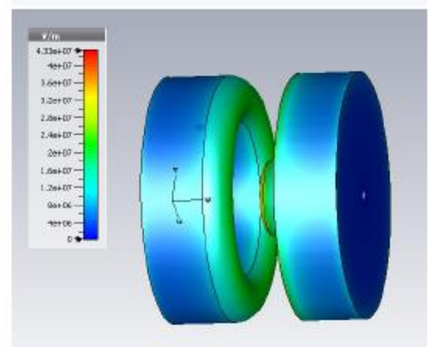
Equipotential Lines and Max EF on focusing electrode

Equipotential Lines and Max Electric Field on focusing electrode





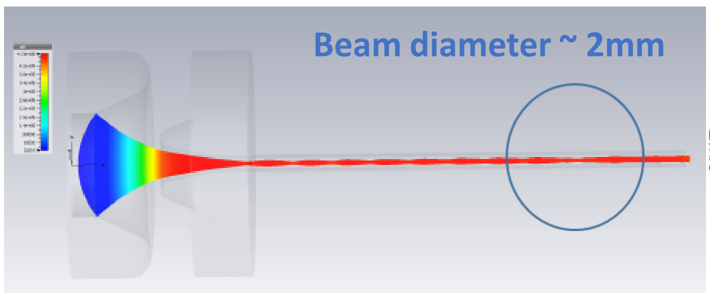
Applied Voltage on cathode (blue)

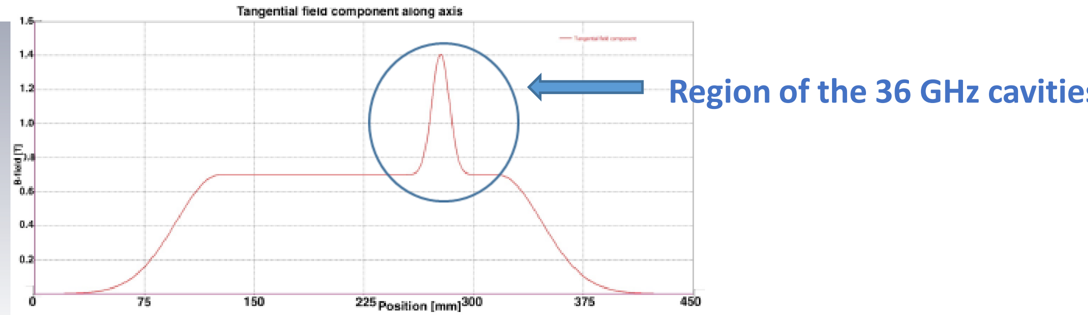


Max Electric Field on cathode (green)

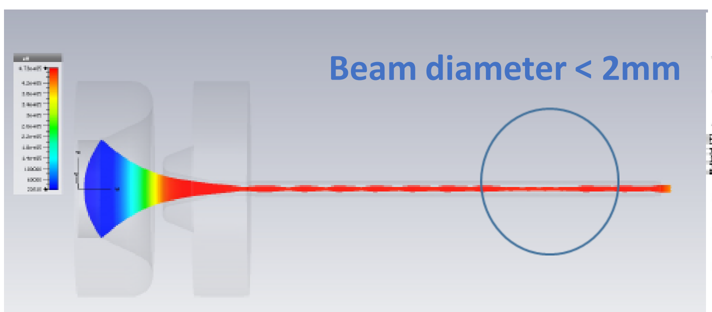
Magnetostatic simulation by CST Particle Studio

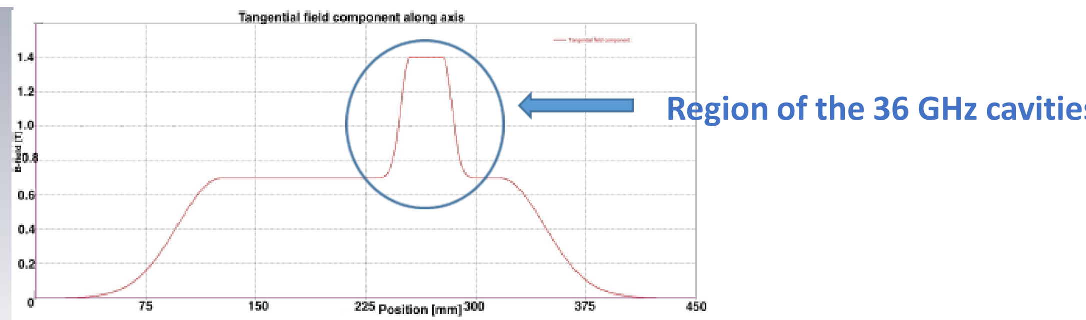
Beam trajectory | **Magnetic field distribution**





Model 1



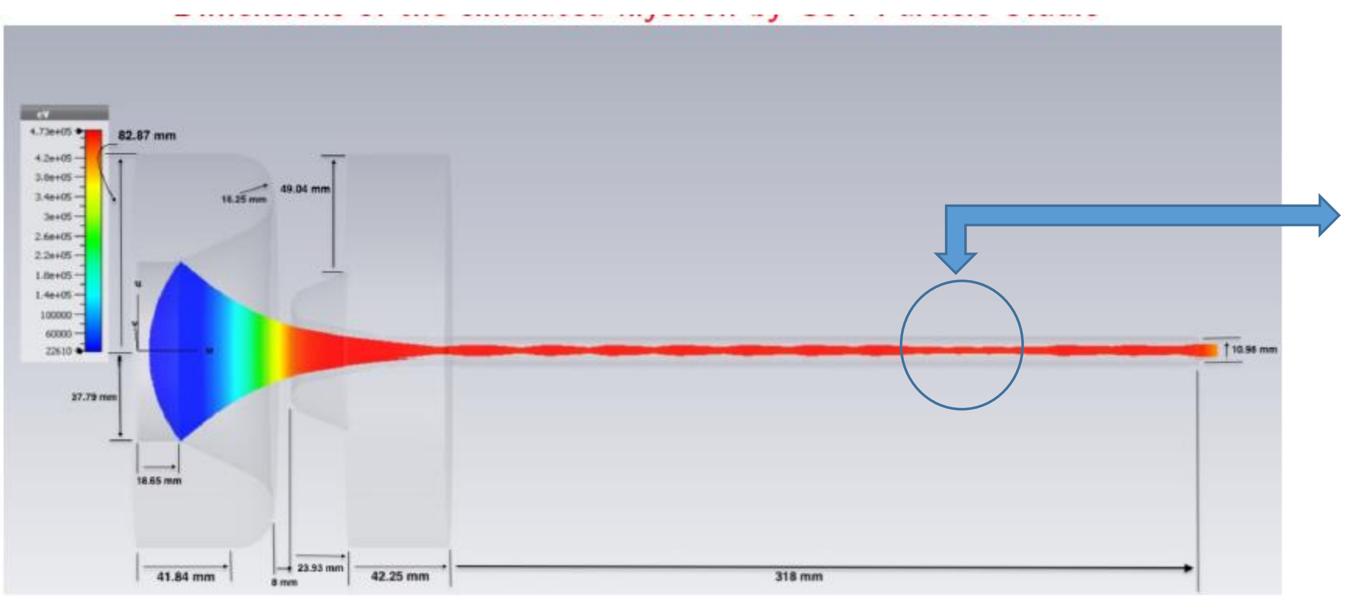


Model 2

In order to install the output RF 36 GHz cavities with a 4 mm iris diameter a tapered tunnel is needed because the bunchers cavities work at about 12 GHz

Dimensions of the simulated klystron by CST Particle Studio

Dimensions of the simulated klystron by CST Particle Studio

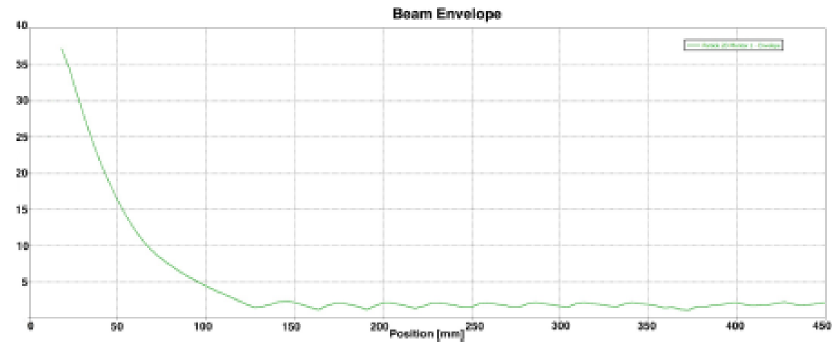


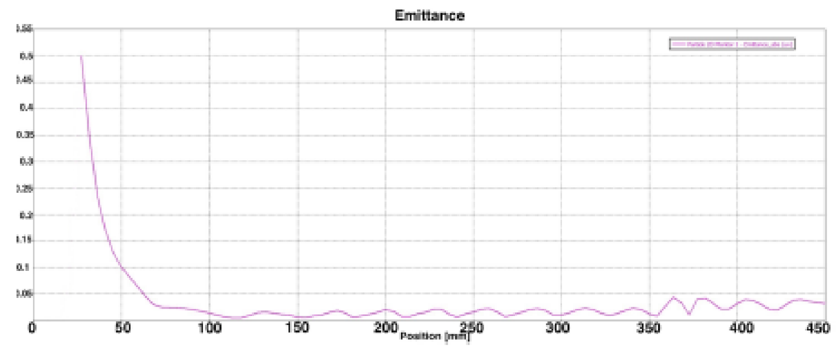
Region of the 36 GHz cavities

Preliminary design parameters of a Ka-band klystron

Design parameters of high power electron 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





The estimations are compatible with the Yale design

Conclusions

Beam dynamics inside the DC gun and Klystron tunnel has been performed

Remake the calculations by using normal conducting solenoid (if it is possible……)

Full 3D analysis including all klystron RF cavities (drive, bunching and output) to be done