DESIGN OF NOVEL RF SOURCES
TO REDUCE THE BEAM SPACE-CHARGE EFFECTS

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ABSTRACT

Traditional rf sources, such as klystrons, TWT require a magnet (such as a solenoid) in order to maintain the electron beam focusing, compensating the particle repulsion caused by space charge effects. We designed a novel rf source with an alternative approach that reduces beam space charge problems. This paper shows the design of the device, with a new formulation of the Child's Law, and the mode-beam stability analysis. The electron beam interaction with the cavity fields has been analyzed by means of particle tracking software and the maximum efficiency of the output cavity has been evaluated.

INTRODUCTION

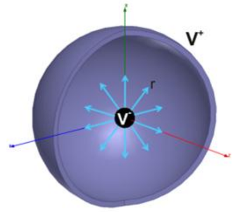

Fig. 1: Spherical cathode with natural expansion of electrons

Reduce space charge problems:
- let the electrons are allowed to propagate in them natural expansion.

Spherical case (Fig. 1):
- Beam generated by a spherical cathode: radial direction expansion.
- The transversal space charge forces are fully balanced.
- No magnet is required to compensate space charge effects.

Cylindrical case (Fig. 2):
- The electrons are generated by a cylindrical cathode (propagating in the radial direction).
- The cavities are coaxial resonators endowed by beampipe apertures.
- The space charge repulsion forces are fully balanced in the φ direction.
- Less magnetic fields will be required to keep the beam focused.
- Remnant space charge effects in the other directions will fast decay when the beam is expanding.

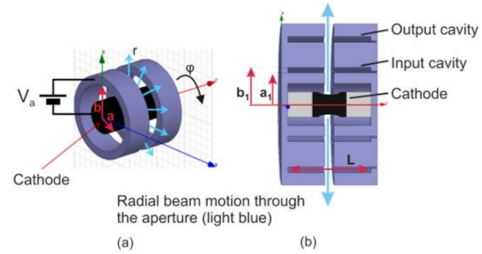

Fig. 2: Cylindrical cathode with radial expansion of electrons (a), Cylindrical klystron with two coaxial resonators (b)

CHILD'S LAW

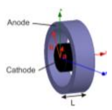

Fig. 3: Cylindrical diode

Purpose: have an analytical esteem of the space charge limited current generated by the cylindrical cathode of Fig. 2(a), approximated by a cylindrical diode composed of two concentric cylinders (Fig. 3) [1] [2] [3-4].

Expression where the distance between the two cylinders are comparable to the radius of the inner cylinder:

$$I_a = \frac{\sqrt{8}\pi V_0}{\eta}\left(\frac{V_a}{V_0}\right)^{3/2}\frac{L}{a}\frac{1}{d^2}\left(\frac{4}{9}+\frac{16}{45}d+o(d)\right)$$

where V_0 = 0.511 MV is the electron rest voltage, $\eta \approx 377\ \Omega$ is the free space impedance, and $d = b/a$. I_a and V_a are the anodic current and voltage, respectively.

MODE STABILITY TEST

Aim: evaluate the stability of cavity crossed by a DC electron beam.

Stability equation:

$$\underbrace{\eta_{eff}V_aI_a}_{\text{Power released by the beam.}} - \underbrace{\frac{\omega U}{V_0}}_{\text{Power lost in the walls.}} < 0$$

Efficiency of the beam power extraction:

$$\eta_{eff} = \frac{<\delta\gamma|_2>}{\gamma-1}$$

Madey's Formula [5]:

$$<\delta\gamma|_2> = -\frac{1}{2}\frac{\partial <(\delta\gamma|_1)^2>}{\partial\gamma}$$

First order perturbation in the beam energy (normalized to mc^2):

$$\delta\gamma|_1 = \frac{e}{mc^2}\int_0^{r_{gap}} E_r cos\left(\frac{\omega r}{c\sqrt{1-1/\gamma^2}}+\phi_{RF}\right)dr$$

Average of the second order perturbation in the beam energy (normalized to mc^2):

$$<\delta\gamma|_2> = -<\left(\frac{e}{mc^2}\right)^2\frac{1}{(\gamma^2-1)^{3/2}}\int_0^{r_{gap}} E_r cos\left(\frac{\omega r}{c\sqrt{1-1/\gamma^2}}+\phi_{RF}\right)dr\int_0^{r_{gap}} E_r\frac{\omega r}{c}sin\left(\frac{\omega r}{c\sqrt{1-1/\gamma^2}}+\phi_{RF}\right)dr>$$

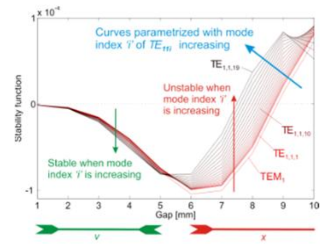

Fig. 4: Stability test in function of the cavity gap

EFFICIENCY

Aim: evaluate the maximum efficiency of the output cavity excited by a perfectly bunched beam (dirac delta), with different current densities I_a/r and anodic voltages V_a.
This test has been performed with a in-house developed FEM simulation and particle tracking software.
We considered an S-band output cavity (f = 2.856 GHz, Q_0 = 20000) and an X-band output cavity (f = 11.424 GHz , Q_0 = 10000).

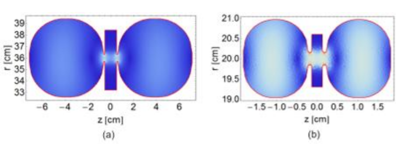

Fig. 5: S-band (a) and X-band (b) cavity FEM simulation, with plot of the electric field

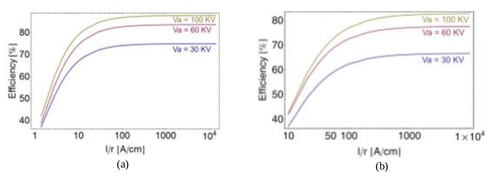

Fig. 6: Maximum efficiencies of the S-band (a) and X- band (b) output cavities

These cavity tests show that the cavities have high efficiencies when the anodic voltage V_a and current I_a are large numbers.
Therefore the cylindrical klystron is suitable for high power rf sources.

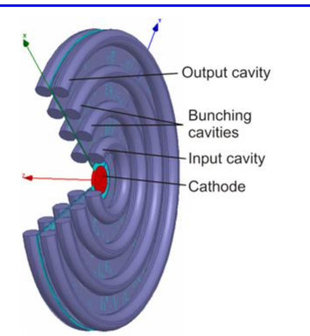

Fig. 7: Overview of the cylindrical klystron

CONCLUSIONS

In multidimensional rf sources, the space charge effects are strongly reduced by letting the electron beam propagate in its natural expansion. The cylindrical klystron is currently under study and design. The cavities are made with coaxial resonators. The stability test method has been presented, showing how the cavity stability varies with the gap. The klystron efficiency showed that this device has higher efficiency with respect the ones available on the market and that it is suitable for making high power rf sources.
The advantages of this new approach in making multi-dimensional rf sources are:
- The beam space charge effects are strongly reduced;
- Less magnetic field is required;
- It is a new way to make sheet-beam klystrons;
- High efficiencies are expected,
- It easily allows to make multi-beam klystrons by having coaxial resonators whose standing wave has multiple oscillations along the `z' dimension of Fig. 2

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