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 Childs 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

Traditional klystrons rf sources work with a focused electron beam that propagates along one preferred direction, interacting with several cavities and elements. To keep the beam focused, those devices require additional focusing elements (such as solenoids that provide a focusing magnetic field) in order to compensate the particle repulsion caused by space charge effects. In this paper we want to propose an alternative klystron design in which the electrons are allowed to propagate in them natural expansion according to the space charge forces. This approach leads to design multidimensional rf sources. If the beam is generated by a spherical cathode, it will expand in the radial direction (considering a spherical coordinate system centered in the cathode center). In this ideal case, the transversal space charge forces are fully balanced (where the transverse dimension is orthogonal to the propagation of each electron). No magnet is required to compensate space charge effects.

We started the klystron design with a cylindrical device that is the easiest case to analyze. The electrons are generated by a cylindrical cathode and equally propagates in the radial direction. The cavities are coaxial resonators endowed by beampipe apertures to let the electrons pass through (Fig. 1). In this novel cylindrical klystron design, the space charge repulsion forces are fully balanced in the φ direction (Indicated in Fig. 1(a)). Moreover less magnetic field will be required to keep the beam focused, since remnant space charge effects acting in the other directions will fast decay when the beam is expanding.

This paper shows the cylindrical klystron fundamentals, a new formulation of the Child's Law and the coaxial mode stability in presence of electrons. The electron beam interaction with the cavities has been analyzed with an in-house developed particle tracking software in order to evaluate the efficiency of the output cavity.

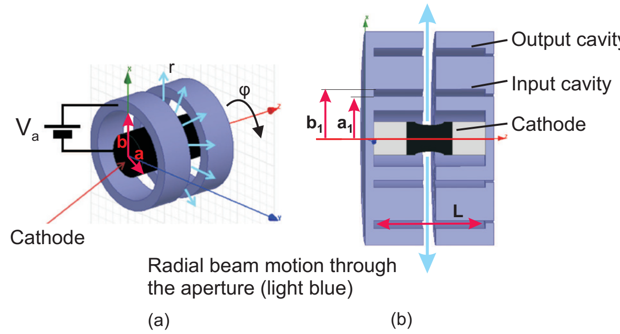

Figure 1: Cylindrical cathode with expansion of electrons (a), Cylindrical klystron with two coaxial resonators (b).

CATHODE CHILD'S LAW

We developed a formula in order to have an analytical esteem of the space charge limited current generated by the cylindrical cathode of Fig. 1(a), approximated by a cylindrical diode composed of two concentric cylinders. This problem was addressed by Langmuir and Blodgett [1], Page and Adams [2], Degond et. al. [3, 4]. In our design, we need an expression where the distance between the two cylinders are comparable to the radius of the inner one. Our expression that represents the current is:

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

where $V_0 = 0.511MV$ is the electron rest voltage, $\eta = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377\,\Omega$ is the free space impedance, a is the radius of the inner cylinder, b is the radius of the outer cylinder, $d = b/a$, L is the length of the cathode. I_a and V_a are the anodic current and voltage, respectively. This expression is used to design the cylindrical cathode.

MODES STABILITY ANALYSIS

In this section we propose a method to evaluate the stability of a single cavity crossed by a DC electron beam. A single cavity can behave like an oscillator self-bunching the electron beam. This happens when the noise or other effects start bunching the electron beam, and the electron beam modulation releases energy to the cavity. The induced electromagnetic field could contribute to further

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electron bunching. If the feedback is positive and the energy released by the beam overcomes the losses, the cavity oscillates. To guarantee the stability, the energy released by the beam ($\eta_{eff} V_a I_a$) must be lower than the dissipated power ($\omega U/Q_0$). The stability equation to analyze is:

$$\eta_{eff} V_a I_a - \frac{\omega U}{Q_0} < 0 \quad (2)$$

where η_{eff} is the efficiency of the beam power extraction, ω the angular frequency, U the stored energy and Q_0 the quality factor of the cavity. We will calculate the efficiency of the beam power extraction with the perturbation method [5]. The efficiency can be expressed as: $\eta_{eff} = \frac{<\delta\gamma|_2>}{\gamma-1}$, where γ is the beam energy normalized to mc^2 and $<\delta\gamma|_2>$ is the average value of the second order perturbation of the beam energy (normalized to mc^2). We divide Eq. (2) by the squared electric field $|E|^2$, obtaining:

$$V_a \frac{<\delta\gamma|_2>}{|E|^2} \frac{1}{\gamma-1} I_a Q_0 - \omega \frac{U}{|E|^2} < 0 \quad (3)$$

The average of the second order perturbation $<\delta\gamma|_2>$ is calculated with the Madey's formula [5]:

$$<\delta\gamma|_2> = -\frac{1}{2}\frac{\partial <(\delta\gamma|_1)^2>}{\partial\gamma} \quad (4)$$

which gives the average of the second order perturbation in function of the first one. The first order perturbation of the beam energy (normalized to mc^2) is given by:

$$\delta\gamma|_1 = \frac{e}{mc^2}\int_0^{r_{gap}} E_r \cos\left(\frac{\omega r}{c\sqrt{1-1/\gamma^2}} + \phi_{RF}\right) dr \quad (5)$$

where e is the electron charge. The average of the second order perturbation formula is evaluated by applying Eq. (4), to Eq. (5), which gives:

$$<\delta\gamma|_2> = -<\left(\frac{e}{mc^2}\right)^2 \frac{1}{(\gamma^2-1)^{3/2}}\cdot$$
$$\cdot\int_0^{r_{gap}} E_r cos\left(\omega\frac{r}{c\sqrt{1-1/\gamma^2}} + \phi_{RF}\right) dr\cdot \quad (6)$$
$$\cdot\int_0^{r_{gap}} E_r \frac{\omega r}{c} sin\left(\omega\frac{r}{c\sqrt{1-1/\gamma^2}} + \phi_{RF}\right) dr >$$

For each mode taken in consideration, the terms $\frac{<\delta\gamma|_2>}{|E|^2}$ and $\frac{U}{|E|^2}$ are calculated by integrating the electric field given by the HFSS [6] eigenmode simulations.

High Order Modes in a Coaxial Resonator

Considering a coaxial resonator without beampipe aperture that approximates the input cavity of Fig. 1(b), the dominant mode is the TEM_1 and its resonant frequency in vacuum is given by: $f_{TEM1} = c/(2L)$. However, high order resonant modes can exist. Let's call $r = (a_1 + b_1)/2$, and $gap = b_1 - a_1$. If the cavity gap is much smaller than the average radius r, the following expressions represent the TE_{mnp} and TM_{mnp} resonant frequencies:

$$f_{TEmnp} \cong \frac{c}{2\pi}\sqrt{\left(\frac{m}{r}\right)^2 + \left(\frac{(n-1)\pi}{gap}\right)^2 + \left(\frac{p\pi}{L}\right)^2}$$
$$f_{TMmnp} \cong \frac{c}{2\pi}\sqrt{\left(\frac{m}{r}\right)^2 + \left(\frac{n\pi}{gap}\right)^2 + \left(\frac{p\pi}{L}\right)^2} \quad (7)$$

Mode Stability Results

We performed the stability test of a coaxial resonator with an average radius r = 134 mm, a length L = 13.12 mm and variable gap from 1 mm to 10 mm. It is crossed by a beam with V_a = 30 kV and I_a = 200 A, which fundamental resonant mode is the TEM_1, at the X-band frequency of 11.424 GHz. We are interested to see if all the resonant modes are stable in function of the cavity gap.

Fig 2 represents the result of the stability test, parametrized with different curves, each one representing a mode. The stability test shows that up to 5 mm of gap,

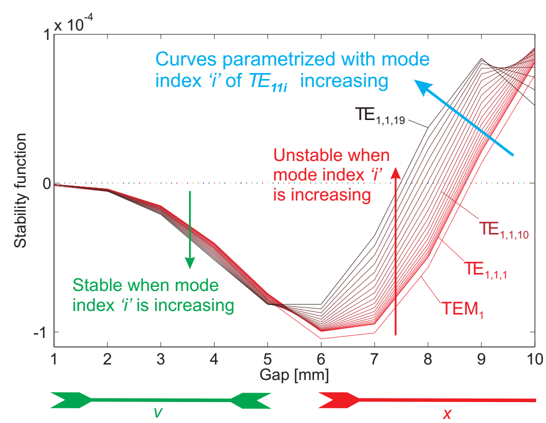

Figure 2: Stability test

all the modes are stable. Starting from the mode TEM_1, $TE_{1,1,1}$ and going up with the mode index i of $TE_{1,1,i}$ the stability function becomes always more negative. On the contrary the cavity become unstable when the gap exceeds 6 mm, because the mode progression shows that the stability function becomes positive. The stability test will be carried out for all the cavity used in the klystron.

KLYSTRON EFFICIENCY

This section evaluates 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, working at the frequency of 2.856 GHz and an X-band output cavity, working at the frequency of 11.424 GHz. The FEM eigenmode simulations of the cavities are depicted in Fig. 3(a) for the S-band case and Fig. 3(b) for the X-band. The edges have

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been rounded in order to obtain high Q cavities, which are Q_0 = 20000 and Q_0 = 10000 for the S-band and X-band, respectively. With the designed cavities, we construct the

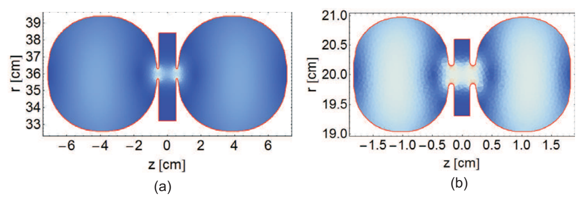

Figure 3: S-band (a) and X-band (b) cavity FEM simulation, with plot of the electric field

efficiency curves, shown in Fig. 4 for the S-band and in Fig. 5 for the X-band. These cavity tests show that the

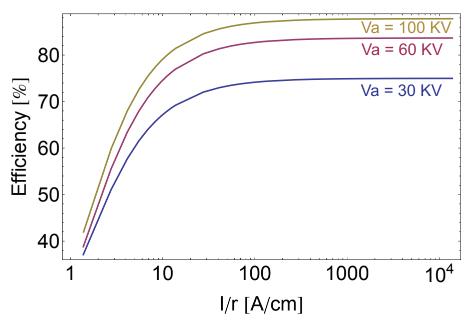

Figure 4: Max efficiencies of the S-band output cavity

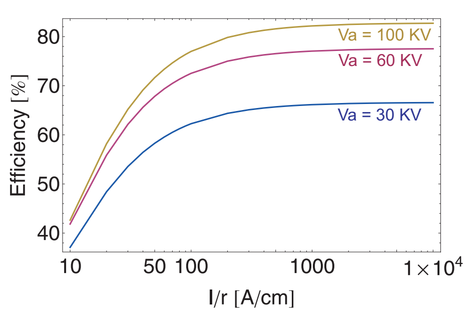

Figure 5: Max efficiencies of the X-band output cavity

cavities have high efficiency when the anodic voltage V_a and current I_a are large numbers. Therefore the cylindrical klystron is suitable for high power rf sources. This test represents the absolute maximum efficiency of the cavities, since it has been carried out by using a perfectly bunched beam. The final device will look like the picture of Fig. 6.

CONCLUSIONS

This paper presented the basic concept of multidimensional rf sources, where the space charge effects are strongly reduced by letting the electrons propagate in them natural expansion. The simplest case of multidimensional rf source is the cylindrical klystron, device that is currently

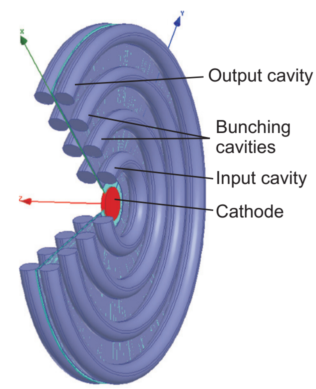

Figure 6: Cylindrical klystron with four cavities

under study and design. The beam generated by a cylindrical cathode interacts with cavities (the input, the bunching and the output one) that are made with coaxial resonators. The stability test method has been presented, showing how the cavity stability varies with the gap. The klystron efficiency has been evaluated in the S-band and the X-band cases, showing 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. 1.

ACKNOWLEDGMENT

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