ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWI003

DESIGN OF A RADIAL KLYSTRON*

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Abstract

The radial klystron is a multidimensional rf source where the beam is generated by a cylindrical gun and it propagates in the radial dimension. The advantage of this design is that the space charge effects are balanced in the azimuthal dimension and a lower magnetic fields is required to focus the electron beam. The bunching is made with concentric coaxial resonators, connected by drift tube. The electron beam interaction with the cavity fields has been analyzed by means of particle tracking software in order to evaluate the beam bunching and the beam dynamics. This paper shows the klystron design, optimizing the shape and the position of each cavity, in order to maximize the efficiency of the device.

INTRODUCTION

The traditional klystron is a linear-beam rf source, where a focused electron beam interacts with resonant cavities. The beam must be focused by a solenoid, to compensate the space charge forces. Gain and efficiencies are limited by the space-charge. It is possible to reduce the space charge effects by allowing the electrons to propagate in the natural expansion according to the space charge forces. This can happen if the beam is generated from a central source (cathode) and it expands in the three-dimensional space (Fig. 1). In this ideal case, the transversal space-charge forces are

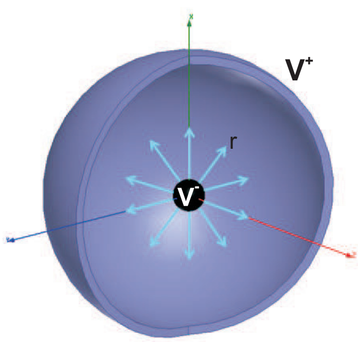

Figure 1: Three-dimensional natural expansion of electrons.

fully balanced (where the transverse dimension is the orthogonal to the propagation of each electron). No magnet is required to compensate space charge effects. This approach uses the multidimensional beam motion to avoid or reduce the space-charge effects.

This paper analyzes a radial klystron [1], which is a cylindrical device. It is the simplest case of multidimensional rf source. The electrons are generated by a cylindrical gun and propagate in the radial direction (Fig. 2(a)). The cavities are coaxial resonators endowed by drift tubes (Fig. 2(b)). The space charge effects are reduced since the

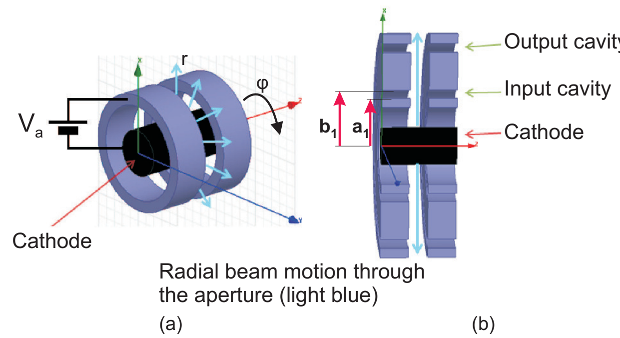

Figure 2: Cylindrical gun with expansion of electrons (a), Radial klystron with two coaxial resonators (b).

electron beam is balanced along the azimuthal direction (Indicated in Fig. 2(a)). Remnant space charge effects will decay when the beam is expanding. A lower magnetic field will be required to keep the beam focused.

This paper presents the ballistic design of a radial klystron. A coaxial mode stability test in presence of electrons have been analyzed. The electron beam interaction with the cavities has been analyzed with an in-house developed particle tracking software. The maximum efficiency of the output cavity has been evaluated with a Dirac delta beam test. Afterwards the whole klystron has been designed.

MODES STABILITY ANALYSIS

This section reports the single cavity stability results. A single cavity crossed by a DC beam can behave as an oscillator. This happens when the noise starts bunching the electron beam. The latter releases energy to the cavity, contributing to further bunching. If the feedback is positive, the released energy overcomes the losses and the cavity self-oscillates. To guarantee the stability a method has been proposed in [2, 3] to evaluate the stability function. When the cavity is stable, the stability function is negative.

A coaxial resonator has been considered. It approximates the input cavity of Fig. 2(b). The fundamental mode is the TEM_1 and its resonant frequency in vacuum is given by: $f_{TEM1} = c/(2L)$. High order resonant modes exist,

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and they must be all stable to guarantee the klystron stability. Let's define $r = (a_1 + b_1)/2$, 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:

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

Mode Stability Results

The stability test has been preformed on a coaxial resonator with an average radius r = 134 mm, 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. The fundamental resonant mode is the TEM_1, at the X-band frequency of 11.424 GHz. We are interested to find the maximum gap condition that assures that all the resonant modes are stable.

Figure 3 represents the result of the stability test, with different curves, each one representing a mode. The stability test shows that up to 5 mm of gap, all the modes are stable. Starting from the mode TEM_1, $TE_{1,1,1}$ and increasing the mode index i of $TE_{1,1,i}$ the stability function is always negative. In these conditions the cavity is stable for all the high order modes. The cavity become unstable when the gap exceeds 6 mm, because the mode progression shows that the stability function has positive values. This test must be repeated for each klystron cavity.

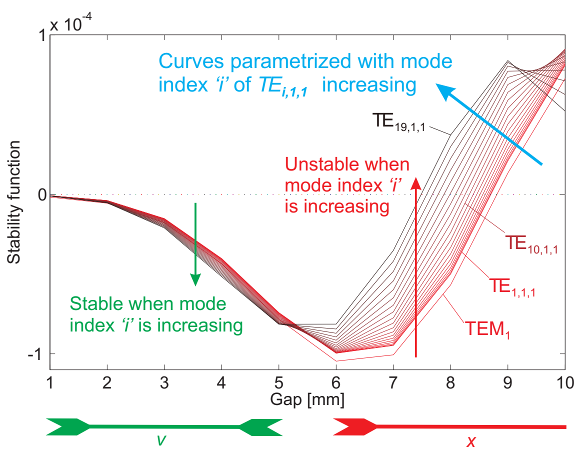

Figure 3: Stability test

KLYSTRON DESIGN

The reduction of the space-charge effects allows to design a klystron with a low anodic voltage. The goal is to have V_a = 30 kV, which allows to use a smaller modulator. At SLAC an X-band prototype of radial klystron is under design. The constrains are: low anodic voltage (30 kV) and high efficiency (higher than 60 %). In the first prototype the generated rf power must not exceed 1 MW, in order not to have problems with the ceramic windows. Therefore the chosen anodic current is: I_a = 40 A. The working frequency is 11.424 GHz. The cavity surfaces have been rounded to minimize losses.

The design has been carried out with an in-house developed FEM simulation code, which calculates the eigensolutions of the cavity fields. The interaction of the electron beam with the cavity fields is achieved with a particle tracking software, in-house developed as well. It takes into account the beam loading. It evaluates the steady-state complex power balance between the power extracted from the beam, the power dissipated in the cavity walls and power transmitted through the output waveguide. With this tool it is possible to evaluate the voltage induced in each cavity, and the beam dynamics. It is possible to evaluate the efficiency of the output cavity, given the electron bunch parameters.

The first step in the klystron design is to optimize the output cavity geometry with a perfectly bunched beam (Dirac delta function). A preliminary analysis shows that, in a radial klystron, the output cavity efficiency depends on the current density ratio I_a/r, the higher, the better. In order to have high efficiencies, the output cavity must be placed in correspondence of an high current density (I_a/r) location. Therefore for a fixed anodic current, the radius of the output cavity (r_{out}) must be small. This can be achieved by placing the output cavity at the smaller possible radius, closer to the center axis, while the input and bunching cavities are outside at higher radius. The electrons must travel in an inward direction, opposite of Fig. 2, starting from an outside cathode, converging into a central anode. In order to allow space for the central anode collector, the output cavity has been fixed at 4 cm.

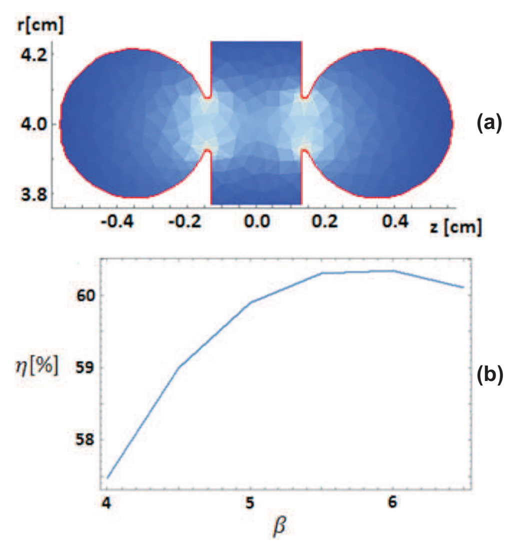

Figure 4: Optimized output geometry (a), efficiency vs. coupling, with one particle beam test (b).

The optimization of the output cavity has been performed with the in-house developed FEM simulation and particle tracking software. Fig. 4(a) shows the optimized

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output cavity geometry, while Fig. 4(b) shows the cavity efficiency in function of the β coupling factor.

After optimizing the output cavity, the whole klystron has been designed. The ballistic optimization has been performed, supposing negligible the space-charge effects. In order to have high efficiency, four cavities are needed. Precisely, an input cavity, a bunching cavity and two output cavities. The power generated by the two output cavities will be combined afterwards. The schematic of the klystron is depicted in Fig. 5, where the couplings of the output cavities are: $\beta_1 = 8.7$ and $\beta_2 = 8.5$. All cavities are tuned at the frequency f = 11.424 GHz.

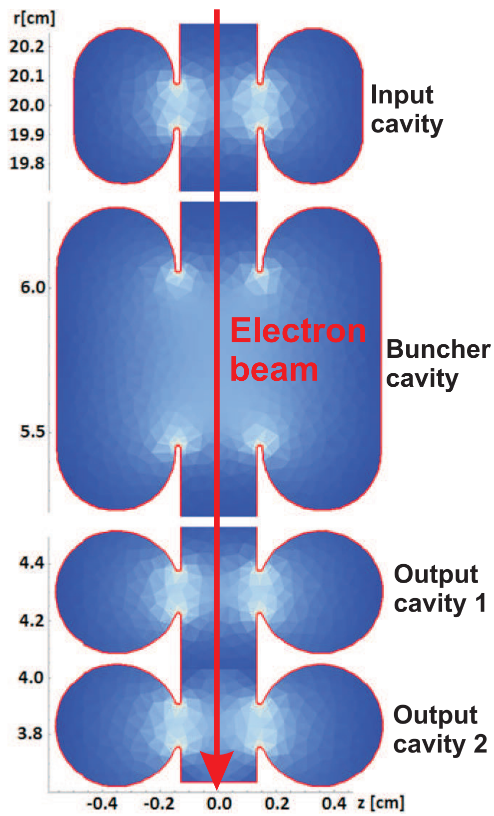

Figure 5: Klystron design. For drawing reasons, the input, bunching and the output cavities are separated.

The sum of the two output cavities efficiencies is 60 % (η_1 = 40% and η_1 = 20 %), producing 30 dB gain with 600 W of input power.

Figure 6 reports the growth of the first harmonic of the current I_1/I_0 (blue) and the growth of the second harmonic of the current I_2/I_0 (red).

Figure 6 shows that the input and the buncher cavities provide a growth in the harmonic currents. The output cavity 1 has been chosen in order to keep an high value of the first harmonic current for the second output cavity. This has been achieved overcoupling the first output cavity.

CONCLUSIONS

Radial klystrons are rf sources where the electron beam travels along the radial dimension. The azimuthal space-

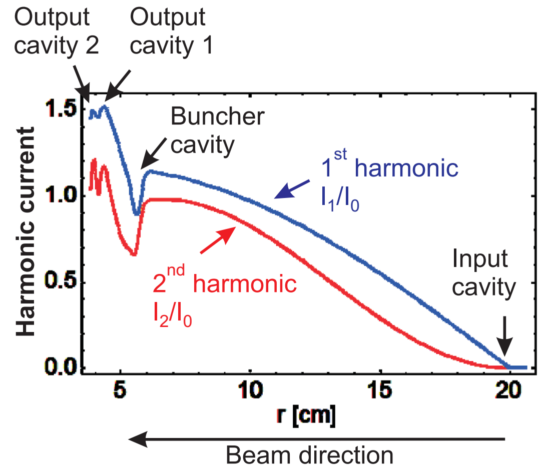

Figure 6: Growth of the first harmonic of the current I_1/I_0 (blue) and growth of the second harmonic of the current I_2/I_0 (red).

charge forces are balanced. The electron beam is generated by a cylindrical gun and it interacts with cavities (the input, the bunching cavities and the output cavity) that are made with coaxial resonators. The stability test method has been presented, showing the cavity stability with respect to the gap value. The optimization of the output cavity has been carried out by using a perfectly bunched beam. The whole klystron has been designed with the ballistic approximation. A total of four cavities has been used, providing 60 % of efficiency at the frequency of 11.424 GHz. The gain is 30 dB.

The advantages of the radial klystrons are:

- The beam space charge effects are reduced;
- High efficiencies are expected;
- It is a new way to make sheet-beam klystrons;
- A lower magnetic field is required;
- It easily allows to make multi-beam klystrons by stack multiple pancakes along the ‘z’ dimension of Fig. 2.

ACKNOWLEDGMENT

Work supported by the US DOE under contract DE-AC03-76SF00515. Patent pending.

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