COLLECTION OF SPENT ELECTRON BEAM BY MEANS OF A SERIES OF DEPRESSED COLLECTORS AND UNWINDING THE MAGNETIC FIELD IN LINEAR BEAM TUBES

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Abstract

In this paper, the spent electron beam in a linear beam tube is collected by depressed collectors by unwinding the magnetic field prior to the collection using refocusing section. It is found that the overall efficiency has considerably increased as compared to that without refocusser, thus, proving that the use of refocusser is a useful addition in the collection of electron beam in linear beam tubes.

Index Terms - *depressed collector, helix t.w.t., magnetic refocuser*

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I INTRODUCTION

A primary consideration in selecting microwave tubes for many applications is the overall efficiency in converting d.c. input power to r.f. output power at the desired frequency. One very important part of overall efficiency of conversion of power in the electron beam to r.f. power is electronic efficiency, which is the efficiency of conversion of power in the electron beam to r.f. power.

Depressed collectors are passive converters of kinetic energy remaining in the spent electron beam into potential energy, thus reducing the power consumed by the tube that would otherwise get converted into heat upon impact. This reduction is accomplished by depressing the potentials of collecting electrode below that of the tube.

In contrast to the laminar flow conditions in a well focused unmodulated pencil-shaped electron beam, a heavily bunched spent beam is turbulent. The spent beam has a much higher degree of disorder than smoother beams with more parallel trajectories. It is obvious that less energy may be recovered by any collector from such a turbulent beam than from a laminar stream. In order for a multistage depressed collector to operate efficiently, the electron beam entering it must not diverge rapidly. Rapid divergence leads to large radial components of electron velocities and to energy components that cannot be recovered by the collector. To reduce the divergence of a beam, it is necessary to expand its diameter so that space charge forces are reduced. A magnetic refocusing system is used for this purpose. The term reconditioning or refocusing is used in this context to describe a simple, passive device that conditions the spent beam prior to its entry into the collector such that first, the space charge is diluted, if necessary, and second, the degree of turbulence is reduced by refocusing the beam to a large diameter.

In this paper, a computer modeling of depressed collection of spent electron beam is done by unwinding the magnetic field in a helix traveling wave tube(t.w.t.).

II SPENT BEAM REFOCUSSING

Prior to injection into multi-stage depressed collectors, the spent beam passes through a magnetic refocuser. The purpose of refocusing is to process the beam by reducing space charge forces in manner that will not increase the turbulence of the beam. In the refocusing section, the beam actually passes through a r.f. free region after the interaction region and then passes through a region with magnetic field in the direction opposite to the prior Brillouin focusing field B_z. This refocuser is different from previously used refocusers[1] in the sense that they decrease the magnetic field very slowly in the refocusing section (solenoidal field) to zero and then use another solenoidal field in the reverse direction until it reaches $-B_z$. Now, at this point, the beam is sufficiently large in diameter as well as laminar. The refocuser which has been used here has static magnetic field in the opposite direction. This arrangement is much more simpler than the other arrangements. The beam expands in the r.f. free region and then further expands in the refocusing region with magnetic field of opposite polarity. The purpose of this is to completely unwind the magnetic field present in the beam so that the beam enters the collector with minimum turbulence and maximum diameter. The electron beam with these qualities is well suited for collection. The spent beam contains electrons of different velocities and thus different energies. Therefore, for a highly efficient collector, it is necessary to examine the energies of the electrons in the spent beam entering the collector. To recover a large fraction of power, the collector is designed to sort the electrons in the spent beam into various energy classes. The electrons in each energy class is collected on electrode at a voltage that recovers as much of energy as possible.

The degree of improvement in the quality of spent beam and hence the overall efficiency depends strongly on the level of modulation, internal tube efficiency and the perveance. The refocuser used here contributes positively by increasing the overall efficiency of the helical traveling wave tube by 7-9 percent for large beam perveance. Therefore, it can be a useful addition in any linear beam tube.

III TWO DIMENSIONAL LARGE SIGNAL ANALYSIS

The r.f. circuit is periodic in both axial and angular directions (biperiodic) and the electron beam is focused by a finite axial magnetic field, radial and angular motion of the electrons being allowed. Following Rowe[2], general Lagrangian methods and numerical techniques have been utilized for solving the integro-differential equations for a given set of input parameters, initial and boundary conditions , by performing forward iterations starting from these input parameters.

The electron beam is divided into a number of annular rings or layers of charge and each layer is further divided into representative charge groups. Three annular rings and 32 charge groups are taken. The working equations are that of Rowe[2]. The nomenclature for the symbols is at the end of the paper.

$$\frac{d^2z}{dt^2} = -\left[E_{sc-z} - \frac{\partial V}{\partial z}\right]$$

(1)

$$\frac{d^2r}{dt^2} - r\left(\frac{d\phi}{dt}\right)^2 = -|\eta|\left[E_{sc-r} - \frac{\partial V}{\partial r} + B_z r\frac{d\phi}{dt}\right]$$

(2)

Here, it is assumed that the magnetic field, B_z is entirely axially directed at the input to the interaction region.

At z=0, from Busch's theorem for the case of Brillouin flow,

$$\frac{d\varphi}{dt} = \eta\frac{B_z}{2} \qquad (3)$$

Using normalized variables,

$$\frac{d\phi}{dt} = u_0\left[\frac{2C}{r}u._{\phi}(y, x_0, \phi_0, \varphi_0)\right]$$

(4)

At y=0 , x=x_0 and $\eta B_z = \omega_c$. Therefore

$$\omega_c = \frac{4C^2\omega}{x_0}u._{\phi}(y, x_0, \phi_0, \varphi_0)$$

$$u._{\phi}(y, x_0, \phi_0, \varphi_0) = \frac{\omega_c}{\omega}\left(\frac{x_0}{4C^2}\right)$$

(5)

The Radial Field equations are

$$\Psi\frac{d^2A}{dy^2}-A\Psi\left(\frac{1}{C}-\frac{d\theta_y}{dy}\right)^2+A\frac{d^2\psi}{dx^2}-\left(\frac{d\theta_x}{dx}\right)^2 Ay$$

$$+\frac{A}{x}\frac{d\psi}{dx}+A\psi\left(\frac{k_l}{C}\right)=0$$

(6)

$$-2\psi\left(\frac{1}{C}-\frac{d\theta_y}{dy}\right)\frac{dA}{dy}+Ay\frac{d^2\theta_y}{dy^2}+2A\frac{d\psi}{dx}\frac{d\theta_x}{dx}+$$

$$A\psi\frac{d^2\theta_x}{dx^2}+\frac{A\psi}{x}\frac{d\theta_x}{dx}=0$$

(7)

The circuit equations are

$$\frac{d^2y}{dy^2}+A\left[\frac{(1+Cb)}{C^2}-\left(\frac{1}{C}-\frac{d\theta_y}{dy}\right)^2\right]=-\frac{2(1+Cb)}{\pi C{x_b}^2}$$

$$\left\{\int_0^{x_b}\left[\int_0^{2\pi}\psi(x)\frac{\cos\phi}{1+2Cu_y}d\phi_0+2Cd\int_0^{2\pi}\psi(x)\frac{\sin\phi}{1+2Cu_y}d\phi_0\right]x_0dx_0\right\}$$

(8)

$$A\left[\frac{d^2\theta_y}{dy^2}-\frac{2d}{C}(1+Cb)^2\right]+2\frac{dA}{dy}\left(\frac{d\theta_y}{dy}-\frac{1}{C}\right)=$$

$$\frac{2(1+Cb)}{\pi C{x_b}^2}\left\{\int_0^{x_b}\left[\int_0^{2\pi}\psi(x)\frac{\sin\phi}{1+2Cu_y}d\phi_0-2Cd\int_0^{2\pi}\psi(x)\frac{\cos\phi}{1+2Cu_y}d\phi_0\right]x_0dx_0\right\}$$

(9)

The relation between variables is

$$\frac{\partial\phi}{\partial y}+\frac{d\theta_y}{dy}=\frac{1}{C}\left[\frac{1}{1+2Cu_y(0,x_0,\phi_0)}-\frac{1}{1+2Cu_y(y,x_0,\phi_0)}\right]$$

(10)

The radial distance x is treated as a independent variable and is written as

$$x(y,x_0,\phi_0)=x_0+2C\int_0^y\frac{u_x(y,x_0,\phi_0)dy}{1+2Cu_y(y,x_0,\phi_0)}$$

(11)

Now , there are 11 equations that are used to calculate the various characteristics of helix t.w.t.

For ω=3.28 GHz , $\omega_{c=}$1.312 GHz

$\omega_{c=}\frac{e}{m}B_z$, B_z = 0.0468 Tesla

This is the minimum amount of magnetic field required to confine the beam. This is called the **Brillouin Field.** The helix t.w.t. program is written in C++ .There is a short drift region before the electrons enter the refocusing section. The ratio between the refocusing section length and the prior drift length is defined as α .

The spent energy distribution curve at the output of the refocusser is shown in Fig.1.The area under the solid and the dotted curves is the total power that can be recovered by multistage depressed collectors with and without a refocusser respectively. To recover a large fraction of this power, the collector must be designed to sort the electrons in the spent beam into various energy classes. Then electrons in each energy class must be collected on an electrode at a voltage that recovers as much of that energy as possible.

The degree of improvement in the quality of the beam and hence the overall efficiency depends strongly on the level of modulation, internal tube efficiency and the perveance. For different beam perveances, the improvement in overall efficiency is different and is maximum for a particular value which will be shown in the following section.

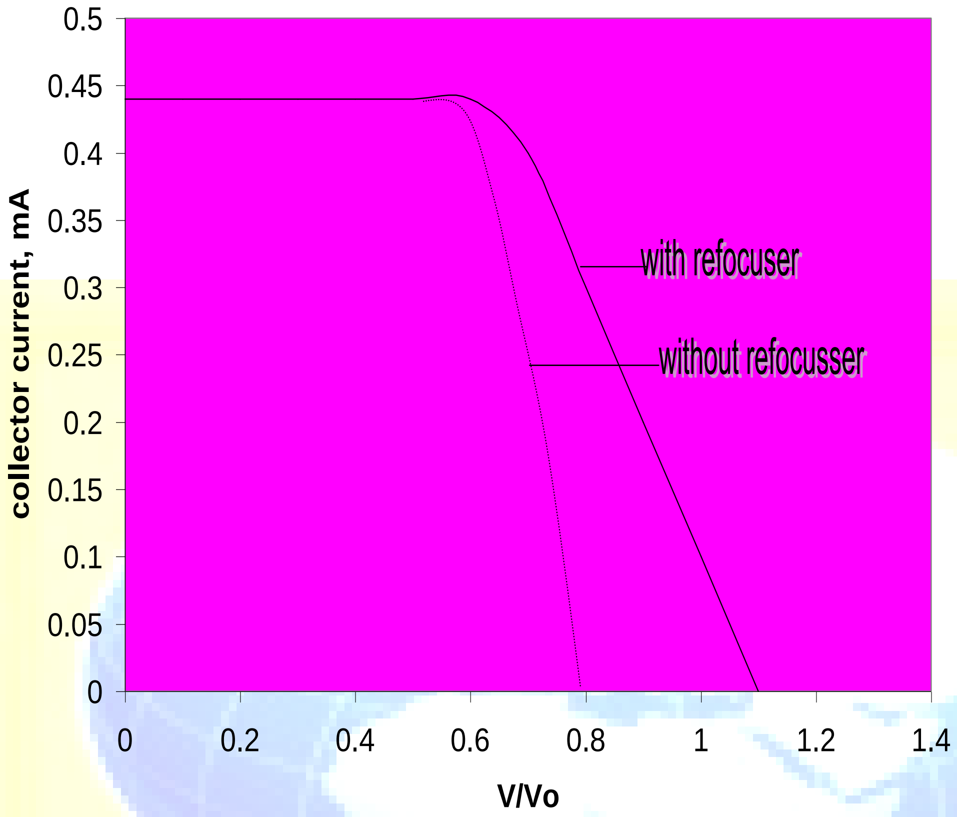

Fig 1. Spent beam energy energy distribution at the output of the refocusing section, μperveance=0.9

IV EFFICIENCY IMPROVEMENT WITH AND WITHOUT THE REFOCUSSER

The overall efficiency , η_{ov}, is given by

$$\eta_{ov}=P_{out}/(P_{in}-P_{rec})$$

where P_{out} is the output power, P_{in} is the input power and P_{rec} is the recovered power through depressed collectors.

Kosmahl[3] presented a simple and accurate method to quickly predict the overall efficiency. His empirical formula has been extracted from Lewis Research Center(LeRC) developed helical t.w.t. program that expresses the lowest (normalized) energy in terms of electronic efficiency and perveance. The true beam-energy distribution curve has been approximated by triangular distribution. It was also assumed that the collector has N depressed stages, including one at the cathode potential which are placed at equal steps. Although the predictions of Kosmahl were quite accurate, they did not give a true picture of the improvement of the overall t.w.t. efficiency as they were based on a number of assumptions. Also, the introduction of beam refocuser before the depressed collectors and its effect on the overall t.w.t. performance was not taken into account.

In the present analysis, the true spent beam characteristics is used to predict the improvement in overall efficiency with and without the refocuser with 4-stage depressed collector.

IV RESULTS AND DISCUSSION

The overall efficiency, η_{ov}, with and without refocuser versus beam perveance is shown in Fig. 2. For cases involving small perveances (< 0.1 μperv), the inclusion of beam refocuser is not very productive in terms of improvement in η_{ov}. But for cases involving large perveances (>0.1 μperv), the inclusion of beam refocuser improves the η_{ov} by 6-8 % which is better as compared to the LeRC results (also shown in the figure for beam perveance < 1.5 μperv. After 4-stages of depressed collectors, the increase in efficiency is negligible and therefore not shown here.

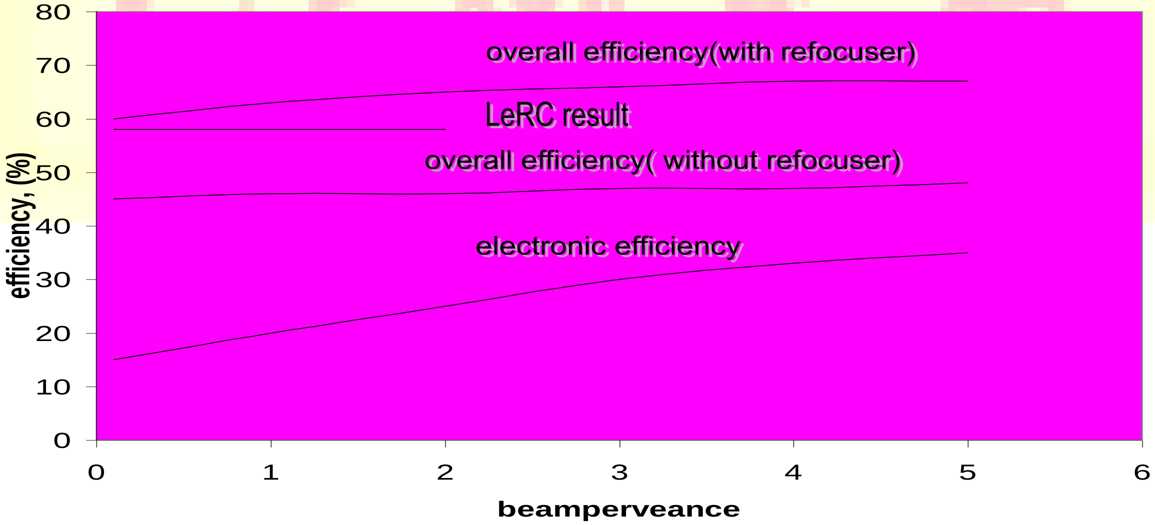

Fig 2. Overall efficiency with and without the refocuser versus beam perveance(μ perv) using 4-stage depressed collector

The variation of overall efficiency, η_{ov}, with α is shown in Fig. 3. It is evident from the graph that for α=0, the efficiency is minimum and increases as α increases but upto a point (α=1.5) and after that remains constant. This can be owed due to beam expansion which increases with greater α and helps in the improvement in the overall efficiency. But as the length of the refocusing region increases, the beam becomes more and more laminar and beam divergence reduces, Thus further increase in α does not contribute in increasing the overall efficiency.

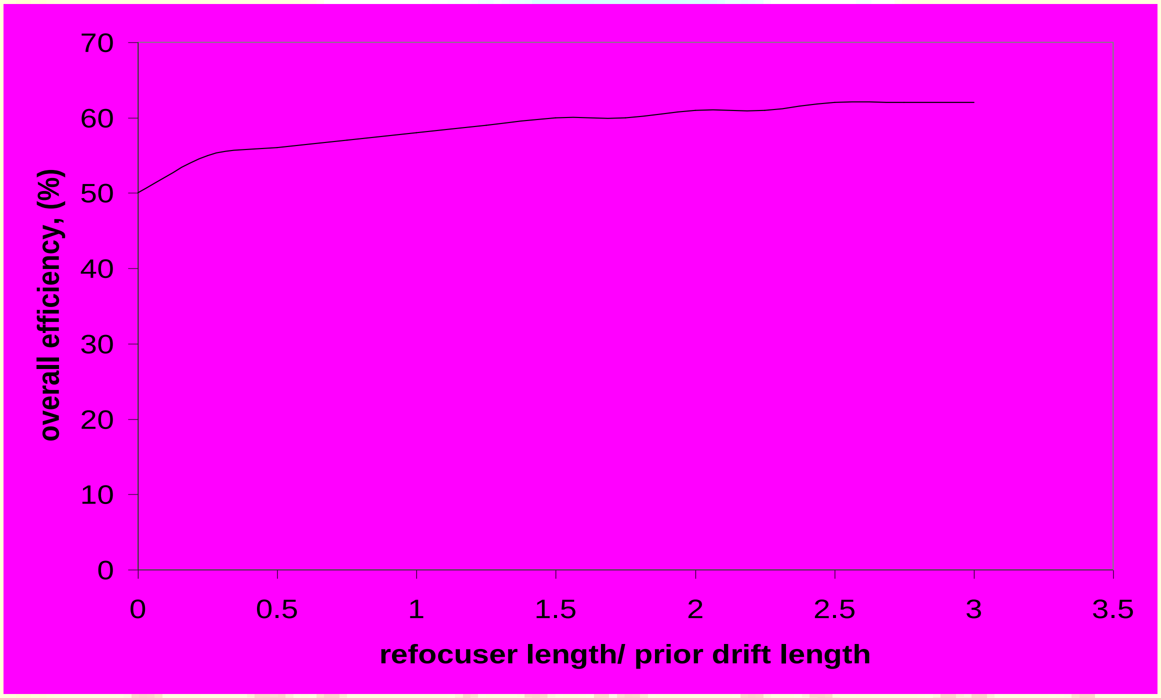

Fig 3. Variation of overall efficiency (with refocuser) versus α(refocuser length/ prior drift length)

V CONCLUSION

It can be concluded from this paper that the refocuser which has been used has contributed positively by increasing the overall efficiency of the helical t.w.t. by 7-9 % for large beamperveances (> 0.1 μperv). Therefore, it can be a useful addition in any linear beam tube setup because of the inherent similarity in their operation.

NOMENCLATURE

$A(y)$	normalized r.f. amplitude
u_o	initial axial velocity
B_0	Brillouin focusing field
η	charge to mass ratio of electron
A_0	the amplitude of the r.f. voltage
b	the relative injection velocity
a	the electron stream radius
x_a	normalized stream radius
x_b	normalized circuit radius
C	Pierce's gain parameter
d	loss factor
QC	the small signal space charge parameter
V_0	with the voltage which the electrons are accelerated
Z_0	the characteristic impedance of the transmission line
Φ_0	the entrance phase of an electron beam relative to the r.f. input
$\theta_y(y)$	the r.f. phase lag of the wave
$\psi(x)$	the radial space charge function
φ	normalized angular distance
u_φ	normalized angular velocity
β	the propagation constant
I_0	the d.c. stream current
k_l	u_0 /c

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