Intense Electron Beams with Centrifugal Electrostatic Focusing

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Abstract: This paper presents analysis of the electron beam propagation in transverse radial electrostatic field. It is shown that combination of the inward and outward forces acting on the beam electrons can create favorable conditions for stable transport of equilibrium high current electron beam without need for the confining magnetic field. Physical mechanisms of the beam formation, transport, and stability are discussed and the criteria for the equilibrium beam transport to occur are given.

Keywords: electron gun; electron beam; beam transport; equilibrium beam; electric field; electrostatic focusing; periodic waveguiding structure

Introduction
Transport of electron beams in periodic waveguiding structures without the use of focusing magnetic field provides great promise to achieving high power RF and microwave amplifiers of light weight and compact size. This paper presents a theory and analysis that show a substantial potential of the centrifugal electrostatic focusing, CEF, to transport high power and current density electron beams without need for the magnetic field. Conceptually, CEF employs transverse radial electrostatic field to confine the boundaries of the rotating hollow electron beam and to provide conditions for equilibrium beam transport. The idea of CEF was considered by J. R. Pierce [1], demonstrated first by L. A. Harris [2], and further investigated by others [3-5]. In the course of analysis, modeling, and computer simulation studies we found that stable propagation of equilibrium electron beam in transverse radial electric field depends critically on the beam launch conditions and the annular beam transport channel dimensions. In this paper we discuss the theory which explains physical mechanisms of the beam formation, transport, and stability and yields analytical relations that describe and allow optimization of the CEF. We also discuss the modeling and computer simulations of CEF configurations for high current and power electron beams and the prospective periodic waveguiding structures for extended beam-wave interaction with the integrated CEF and therefore not requiring the focusing magnetic field.

Focusing in Transverse Radial Electrostatic Field
The central idea of CEF is to create and balance the outward force acting on the beam electrons with the inward force as illustrated in Fig. 1. Having the injected electron beam with the initial azimuthal momentum (velocity $V_\theta$ shown) results in the outward centrifugal force $F_2$ as the rotating hollow beam propagates through the focusing structure. The transverse radial electric field $E_r$ formed in between the coaxial cylindrical conductors under the applied electric potential $U$ in turn produces the inward centripetal force $F_1$, which is to balance the abovementioned outward centrifugal force $F_2$ with the respect of other forces $F_3$ arising due to the beam space charge.

Figure 1. Focusing of electron beam in transverse radial electrostatic field. The electron beam is shown schematically with the straight inner and outer boundaries that correspond to stable transport of the equilibrium beam. If the beam is non-equilibrium the boundaries become rippled. If the beam transport is unstable the boundaries become expanding. An individual beam electron $(e, m)$ with axial velocity $V_z$ is shown in cylindrical coordinates $r, z, \theta$.

Following this model we can consider the beam propagation in the transverse radial electrostatic field, determine the equilibrium beam transport conditions, and find the fundamental limits including parametric optimization of the CEF.

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Intense Electron Beam in the CEF Channel

We describe the transverse motion of the beam electrons based on the equation for the total radial force

\[ F = F_1 + F_2 + F_3 \]

with the account of the relativistic effects and the effects of the conducting walls and the beam rotation on the resulting electromagnetic field produced by the beam space charge. This yields two key equations for the beam outer and inner boundaries, respectively. From these equations the conditions are obtained at which both boundaries have vanishing ripples that sets the sought equilibrium beam transport criteria. In the parametric study we determined combinations of the CEF parameters such as the beam lunch conditions and the annular channel radii that allow maximum beam current and power for stable transport of the equilibrium beam. An example optimized configuration suitable for the future W-band devices is shown in Fig.2. This derived configuration is confirmed by simulations with the 2D/3D charged particle optics finite element code MICHELLE [6]. The electron trajectories in the annular beam transport channel obtained from the simulations are seen in Fig. 2 as a number of colored lines. The pattern of the trajectory lines indicates that the beam remains laminar while propagating through the focusing channel.

Figure 2. Optimized CEF configuration allows stable transport of 167 kW near-to-equilibrium beam at the 21 keV energy, 8 A current, and 327 A/cm\(^2\) current density. Colors represent the current in the beam annular layers. The image is radially stretched.

An example periodic wav guiding structure for extended beam-wave interaction with the CEF is shown in Fig. 4. It has inner conductor, which forms focusing channel in the beam tunnel. The eigenmode analysis shows the comparable field levels as compared to the known RF circuits without inner conductor. This translates to the R/Q values of 1.2 k\(\Omega\) versus 1.4 k\(\Omega\) at the 100 GHz frequency of the commonly used 2\(\pi\)-operating mode, respectively.

Figure 3. The equilibrium beam transport conditions obtained for the 0.2 mm beam annulus width.

Figure 4. Model geometry of an example extended interaction klystron type periodic structure with the integrated CEF.

References