Design of a Multi-Sections Solenoid for Power Microwave Tubes

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ABSTRACT — **The design of a multi-section solenoid to be used in a power TWT focusing structure is presented in this paper. Considerations about material selection, cooling and magnetic aspects are discussed. From Biot-Savart law, it was possible to obtain an equation that describes the axial magnetic density flux profile of this kind of device taking into account the conductor finite length and the dielectric thickness. The electron paths for a beam of 4 A accelerated with 30 kV were evaluated, using a 3-D particle-in-cell code, under influence of the multi-sections solenoid focusing structure being the magnetic density flux changed from 87.5 to 350 mT.**

Index Terms **— Magnetic electron beam focusing, PPM focusing, solenoids.**

I. Introduction

The development of magnetic focusing structures used in linear beam microwave tubes to focus a given electron beam is a peculiar task and the investigation of solenoids or permanent magnets becomes inevitable.

Although its working is simple, the design of a special solenoid involves several areas of science. As example, one can mention electrical engineering, where it is necessary to describe the magnetic density flux profile under actual operation conditions and material engineering, because one must know the properties of the elements (or compounds) so that the device can be employed successfully.

An important characteristic of the solenoids is its heating, by Joule effect, which commonly demands the use of a cooling system. Staprans [1] indicated that cooling must be provided for most electromagnets. For fields higher than 500 G (50 mT), liquid cooling systems are usually necessary.

A possible design that can be obtained experimentally consists in a device constituted by *n* sections, where each one of them is electrically isolated and water-cooled, as presented in Fig. 1. The first advantage of this kind of solenoid, identified from now on as multi-sections solenoid is that its length can be modified any time when one or more sections are disconnected, so that it can be used in different applications. Its theoretical analysis can be carried out considering all the actual physical dimensions of the conductor (mainly its finite length), and dielectric thickness. One must also expect this device is able to supply a periodic magnetic density flux profile, once the electric current can flow for each section with the inverse polarity. This is an attractive solenoid feature due to the possibility to simulate experimentally a PPM (Periodic Permanent Magnet).

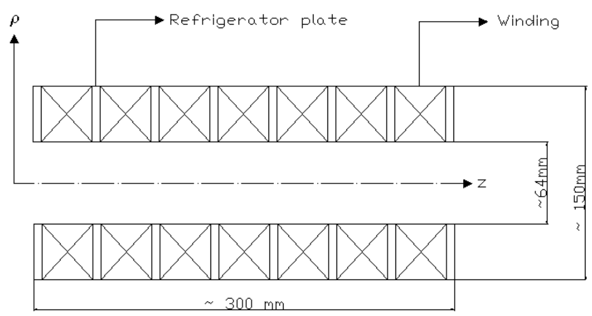

Fig. 1. Schematic design of a multi-sections solenoid. It is indicated windings, cooling plates, and dimensions.

This paper is organized as follows: Section II describes the design of the muti-sections solenoid. Section III shows and discusses the results of the theoretical evaluation of the magnetic field profile and the investigation carried out using the KARAT® [2] code. Section IV relates the conclusions.

II. Design and Specifications

A. Conductor material

The material conductor choice is relevant during the design of a multi-sections solenoid due to its resistivity. It is necessary to use a material with low resistivity to ensure low thermal dissipation. So that it was chosen electrolytic copper (99.97%) in a thin sheet shape.

B. Dielectric Material

In this kind of solenoid, it is necessary to use between overlapped copper turns a dielectric material to avoid short-circuit. This material must provide a high temperature resistance because it must maintain a thermal stability during the device working due to the Joule effect and the varnishing. Considering these situations, the material chosen was a polyester thin sheet.

C. Cooling

The heating of a multi-sections solenoid is a serious problem and must be analyzed carefully. In this kind of device, it is desirable that the cooling liquid flows for every section simultaneously at same temperature. This can be made by means of the parallel copper dishes located at the end of each section. These dishes must be specially machined so that it is possible that the cooling liquid pass through it, extracting the heat generated by the Joule effect of the multi-sections solenoid. It is possible to notice the thickness of this dish and the material that constitutes it are important choices related to the thermal behavior of the device. However, one must keep in mind that the thickness of these pieces will also influence the magnetic density flux profile because it will impose a gap between adjacent magnetic active sections and thus must exist a trade-off relation between thermal and magnetic design.

Besides, one must be also careful with the cooling liquid purity. When impurities are combined with surfaces at high temperatures originating from the multi-sections solenoid and the TWT, it can be induced chemical reactions that makes possible the corrosion of materials and the formation of solid agglomerates which impede the liquid circulation path, reducing the assembly lifetime [3]. Because of economical reasons, it was chosen deionized water as cooling liquid.

D. Magnetic design

The magnetic design of a solenoid must attend to the specifications of its application. In this design the solenoid must be able to provide enough magnetic density flux to confine a TWT electron beam accelerated with 30 kV and with electric current of 4A (data used for the simulations presented below). The microwave device uses a Brillouin focusing system, where the cathode is magnetically shielded. One can evaluate the magnetic density flux using the following equation [4]

$$B_{Br}^2 = 0.69\times10^{-6}\,\frac{I_0}{b^2 V_0^{1/2}}\,, \qquad (1)$$

where B_{Br} is the Brillouin magnetic density flux, I_0 is the electric current, b is the beam radius, and V_0 is the acceleration potential (all quantities must be given in MKS system). Using (1) and considering the RF defocusing problem and possible aberrations B_{Br} must be around 170 mT. Thus, it is necessary to determine the number of turns and the current feed which makes possible to obtain the properly focusing structure.

III. Results and Discussion

A. Theoretical evaluation of the magnetic field profile

The magnetic density flux on axis of symmetry of one sheet turn (elementary unity that constitutes the multi-sections solenoid) is determined from the Biot-Savart law

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\vec{J}(\vec{r}\,')\times(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3}\,d^3\vec{r}\,'\,, \qquad (2)$$

where μ_0 is free-space magnetic permeability, $\vec{J}(\vec{r})$ is the current density, $\vec{r}\,'$ is the source point, and $\vec{r}$ is the field point.

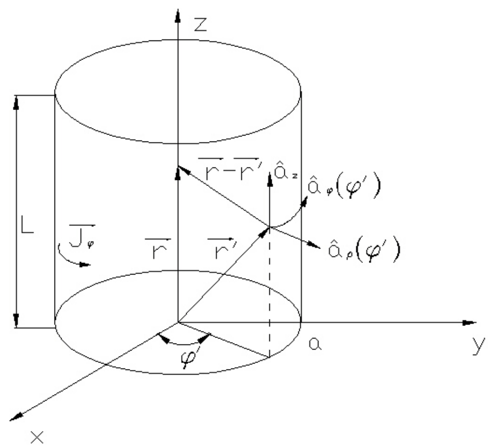

Fig. 2. Geometry used to describe the magnetic density flux produced by one conductor sheet turn.

After a vector analysis of the geometry shown in Fig. 2, considering that the contribution of trigonometric functions will be null because of the integration limits used, it is possible to obtain

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_0^\infty \rho'\,d\rho'\int_0^{2\pi} d\varphi'\int_0^L dz'\,\frac{\left(aJ_\varphi\,\hat{a}_z\right)}{\left[(z-z')^2+a^2\right]^{3/2}}\,, \qquad (3)$$

where $\vec{r}' = a\hat{a}_\rho + z'\hat{a}_z$. The volume element in the cylindrical system is $d^3\vec{r}' = \rho' d\rho' d\varphi' dz$. J_φ is the surface current density in $\hat{a}_\varphi$ direction, z is the axial distance, and a is the turn radius. The surface current density can be given by

$$J_\varphi = \frac{I}{L}\delta(\rho - a)\hat{a}_\varphi(\varphi), \quad (4)$$

where $\delta(\rho - a)$ is the Dirac delta function, and I is the electric current that flows through a conductor sheet of length L as indicated in Fig. 2. Using (4) in (3) and solving the integral of φ', one obtains

$$B = \frac{\mu_0 I}{2}\frac{a^2}{L}\int_0^L \frac{dz'}{\left[(z - z')^2 + a^2\right]^{3/2}}. \quad (5)$$

Solving (5), the magnetic density flux produced by a current sheet of radius a and length L, where circulates an electric current I, is

$$\vec{B}(z) = \frac{\mu_0 I}{2L}\left[\frac{z}{\sqrt{z^2 + a^2}} - \frac{z - L}{\sqrt{(z - L)^2 + a^2}}\right]\hat{a}_z. \quad (6)$$

Using (6), it is possible to determine the axial magnetic density flux of a section that constitutes the multi-sections solenoid made with N turns, considering the sheet and the dielectric thickness. Thus, (6) can be written as

$$B_{section}(z) = \frac{\mu_0 I}{2L}\sum_{i=1}^{N}\left[\frac{z}{\sqrt{z^2 + a_i^2}} - \frac{z - L}{\sqrt{(z^2 - L^2) + a_i^2}}\right], \quad (7)$$

where the parameter a must be changed for every turn. Equation (7) allows one to design a sheet multi-sections solenoid with any arbitrary number of sections if the distance between two of them is known by means of the superposition principle.

The calculated profile of the axial component of the magnetic density flux (B_z) with all sections connected with I =1A and 680 turns (determined by means of electron beam focusing design) is presented in Fig 3. It can be noticed that it is similar to those reported in literature [5-6] and as expected, B_z is larger in the central region than at the ends. A flat top B_z with peak value of 18.5 mT with a 5% fluctuation over length of 150 mm was obtained. Using a current of 10 A, the proposed arrangement is suitable to provide the magnetic field necessary to focus the TWT electron beam.

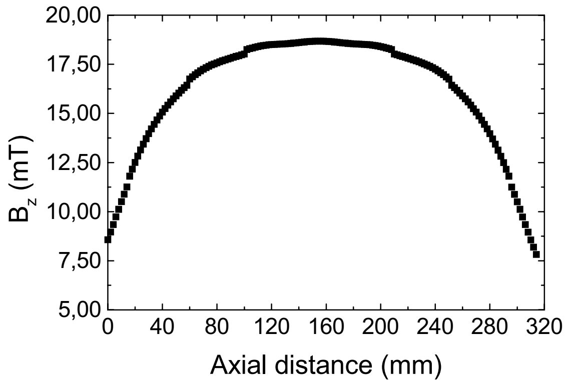

Fig. 3. Theoretical axial component of the magnetic density flux for the multi-sections solenoid designed with I=1A.

B. Theoretical evaluation of the multi-sections solenoid using KARAT® [2] code

Simulated TWT electron beam paths focused by means of the multi-sections solenoid designed with several B_z values are presented in Figs. 4 to 6.

In Fig. 4 is presented the electron beam path under focusing with 87.5 mT. One can notice that the beam does not keep its original radial dimension during traveling and this is an undesirable situation for TWT devices. The existent ripple is originated from the reduced value of the magnetic density flux. In the same figure, it is also presented the magnetic field lines of the multi-sections solenoid. As expected, at the entrance of the focusing structure there are both components of the magnetic density flux (radial and axial). However, when the beam reaches an axial distance of about 6 cm, the radial component of the magnetic density flux is very smaller when compared with the B_z value (this can be noticed by means of the slope of the magnetic field lines).

In Fig. 5 is shown the electron beam path under B_z=175 mT. It is possible to notice that in this situation the beam radius keeps its dimension near to the entrance value along the drift tube length, although a small ripple is seen. The magnetic field lines profile is also shown and is similar to that explained above because the B_z value was the only parameter changed.

In Fig. 6, it is presented the electron beam path for B_z=350 mT. The ripple reported of the previous case became smaller as the magnetic density flux increases. However, the electric current necessary to obtain this result is extremely high and due to electric power reasons, the second case is more attractive to be used.

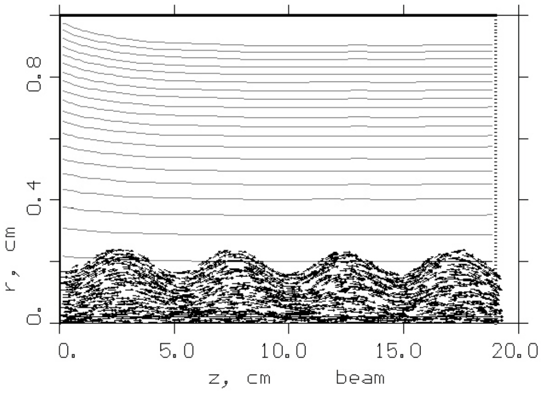

Fig. 4. Simulated TWT electron beam path focused by means of the multi-section solenoid designed (magnetic density flux of 87.5 mT).

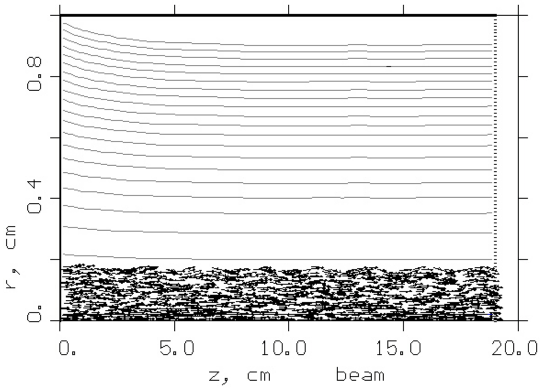

Fig. 5. Simulated TWT electron beam path focused by means of the multi-section solenoid designed (magnetic density flux of 175 mT).

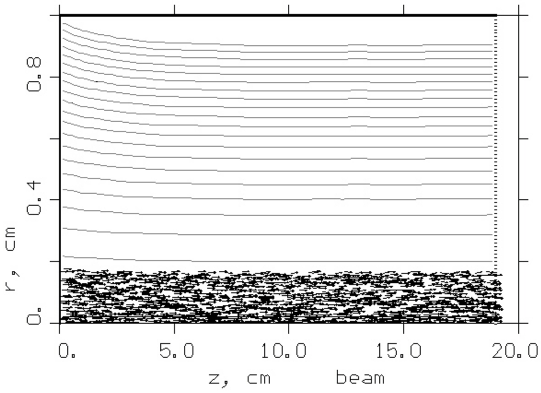

Fig. 6. Simulated TWT electron beam path focused by means of the multi-section solenoid designed (magnetic density flux of 350 mT).

IV. Conclusion

In this paper, it was presented the design of a multi-section solenoid that will be employed as a magnetic focusing structure of a power TWT. Relevant aspects of the device design were discussed and it was possible to obtain a high quality final product taking into account low cost solutions.

The theoretical developed model also presented is physically suitable and its results will be confirmed as soon as possible. It is important to point out that during its development, any approximation was carried out.

The theoretical axial component of magnetic density flux profile is showed and it agrees with the plots reported in literature. To design a full multi-section solenoid, it is necessary to evaluate the magnetic behavior of just one section because of the superposition principle.

It was also presented the TWT electron beam path focused using the multi-sections solenoid designed with several B_z intensities. The results were satisfactory for 175 mT and experimental tests will be carried out soon. Besides, one must keep in mind that using KARAT® [2] and the developed theoretical model, any multi-sections solenoid can be designed and evaluated in actual operational conditions theoretically, reducing considerably the costs.

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References

[1] A. Staprans, E. W. McCune, J. A. Ruetz, "High Power Linear-Beam Tubes", *Proc. of the IEEE*, vol. 61, no. 3, pp. 299-330, March 1973.

[2] V. P. Tarakanov, User's Manual for code KARAT®, Berkeley Research Associates, Springfield-CA, USA, 1994.

[3] CPI. Developed by Communications & Power Industries, 1995-1998. Application Notes: Cleaning and Flushing Water and Vapor-Cooling Systems. Available in: http//www.cpii.com/mpp/company_info/PDF/AEB_32.pdf Access: 20 jul. 2004.

[4] B. N. Bazu, *Electromagnetic Theory and Applications in Beam-Wave Electronics,* Singapore: World Scientific, 1996.

[5] W. G. Worcester, A. L. Weitzmann, R. J. Townley, "Light weight aluminum foil solenoids for traveling-wave tubes", *IRE Trans. Electron Devices*, pp. 70-74, 1956.

[6] B. D. Cullity, *Introduction to Magnetic Materials*, Massachusetts: Addison Wesley Pub. Co., 1972.