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Technology Offer

Advanced collector sweeping with homogenous power deposition of the electron beam in high-power rf vacuum-tubes

Ref.-No.: 1801-3749-WT

This invention includes two alternative advanced methods to achieve a homogenous collector power distribution, which improves the collector capability of high power vacuum-tubes by a factor of two as compared to conventional methods. Furthermore the applied method has a high flexibility to vary the power distribution over a wide range of profiles and match the deposition profiles to different designs of collectors in existing or future electron tubes.

Background

1. Objective:
Improvement of the electron beam collector capability of high-power vacuum tubes by generation of a homogenous beam power distribution with a new collector sweep system.

2. Motivation:
Collector sweep systems, which generate a homogenous power distribution (or a tailored one for non-cylindrical collectors) do not exist at present. Such a system is important for the development of rf-tubes with higher power (towards 2 MW and beyond), because an increased collector capability is required in such tubes. Advanced collector sweeping is also advantageous for state of the art MW-class tubes, because they can be designed more economically (smaller collectors) or operated with higher safety margin (higher lifetime).

3. State-of-the-art collector sweeping technology:
High power millimeter wave vacuum tubes operate with an rf-power of typically 1 MW in cw-mode with an efficiency of 30 -50 %. In this range of efficiencies typically 1-2 MW power remains in the electron-beam after the electron-wave interaction as waste power and must be dissipated in the collector. Because of the favorable cooling properties, such high- power collectors are generally made from copper and have strong sophisticated water-cooling systems for continuous operation. Typical examples are high-power microwave generators, so called gyrotrons (state of the art: output power 1 MW, cw, frequency 140-170 GHz, efficiency 45 %), which are under worldwide development towards even higher power. In such devices, the electron beam is axis-symmetric and hollow. The electrons have an energy of typically 80 - 100 keV and are guided by an axis-symmetric strong (typically 5-6 T) stationary magnetic field towards a axis-symmetric collector, which has a cylindrical shape in the most simple case.

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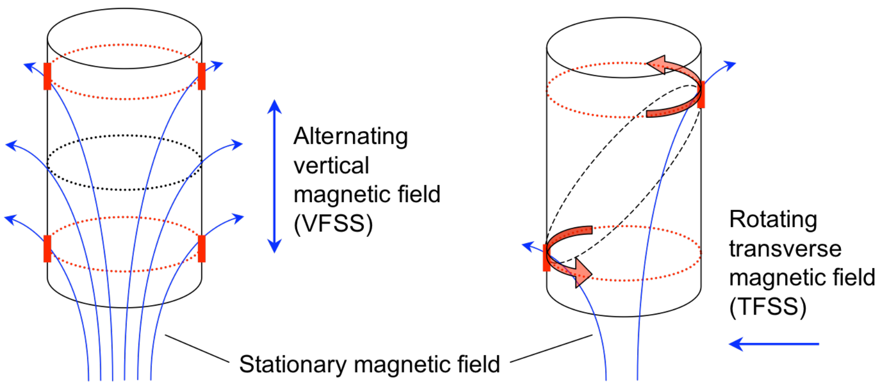

Fig.1: Principle sketch of a Vertical magnetic Field Sweep System (left). The dotted rings mark the upper and lower turning points with collector sweeping, the central ring is the intersection area where the electrons hit the collector without sweeping. The Transverse Field Sweep System is sketched on the right. The intersection area is an ellipse, which rotates with the sweep frequency.

The diverging magnetic field lines and thus the drifting electrons intersect at some vertical position with the collector wall. The strike area forms a horizontal ring with a typical power density of 20 MW/m2. This power density is far beyond existing cooling technology and would lead to melting of the collector.
Thus, commercial gyrotrons [1,2] are equipped with a magnetic field sweeping system, which sweeps the electron-beam over the collector surface to reduce the local power- density in a time average. The commonly used and well established 'Vertical Field Sweeping System' (VFSS) as well as a 'Transverse Field Sweep System (TFSS, invented in Russia [3] and further investigated at FZK [4,5]) are sketched in Fig. 1.
The power distribution obtained with either method, however, shows a strongly inhomogeneous electron-beam power distribution with pronounced maxima as seen in Fig.2.

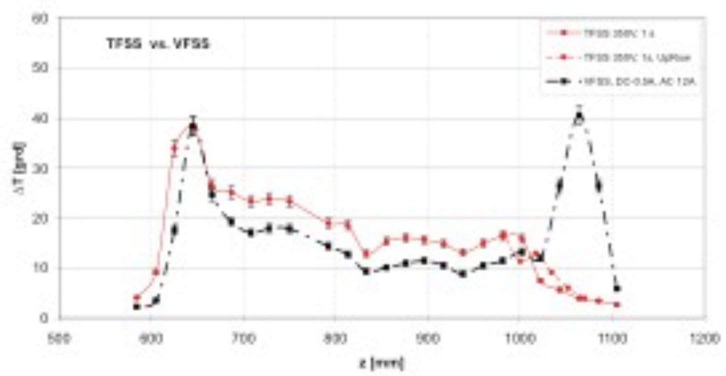

Fig.2: Vertical profiles of the collector temperature increase for TFSS (dots) and VFSS (squares). The power peaking is a general feature of both systems and is the main disadvantage, because the power density in the maximum of the power distribution determines the overall collector capability. Furthermore, the VFSS, which is used in all commercial Gyrotrons, is electrically inefficient because the copper collector represents a single turn, short-circuited coil, which is shielding the sweep magnetic field very efficiently. Powerful AC-power supplies in connection with large, water cooled sweep coils are therefore required to provide the necessary sweeping capability.

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Technology: Advanced collector sweeping

The pronounced power deposition maxima, which are present in both the VFSS and the TFSS for principle reasons can be avoided and a homogenous distribution is obtained by the following methods, which are basically equivalent:

Method (a): The rotating magnetic field from fast TFSS (50 Hz) is modulated with a slow vertical (e.g. 7 Hz) magnetic field as sketched in Fig. 3 (left).
The strike-line ellipse formed by the TFSS is shifted up and down and the peaks of the power deposition profile are smoothed out by the slow periodic vertical displacement. The ellipse rotates many times (typically 10 times) until on vertical cycle is completed. A smooth and homogenous power deposition profile is obtained by adjusting the amplitude and frequency of both sweep systems. A small vertical DC-magnetic field is added for fine-tuning.

Method (b): The fast rotating magnetic field from TFSS (e.g. 50 Hz) is operated with a low frequency amplitude modulation (e.g. 7 Hz), which ideally has a triangular envelope and typically 50 % modulation depth. In this case the tilt angle of the rotating strike line ellipse is slowly modulated as sketched in Fig. 3 (right), thus smoothing out the power peaks. Method (b) has the additional advantage of technical simplicity, i.e. no vertical coil system is required in principle, although a small vertical DC-magnetic field is advantageous for fine-tuning.

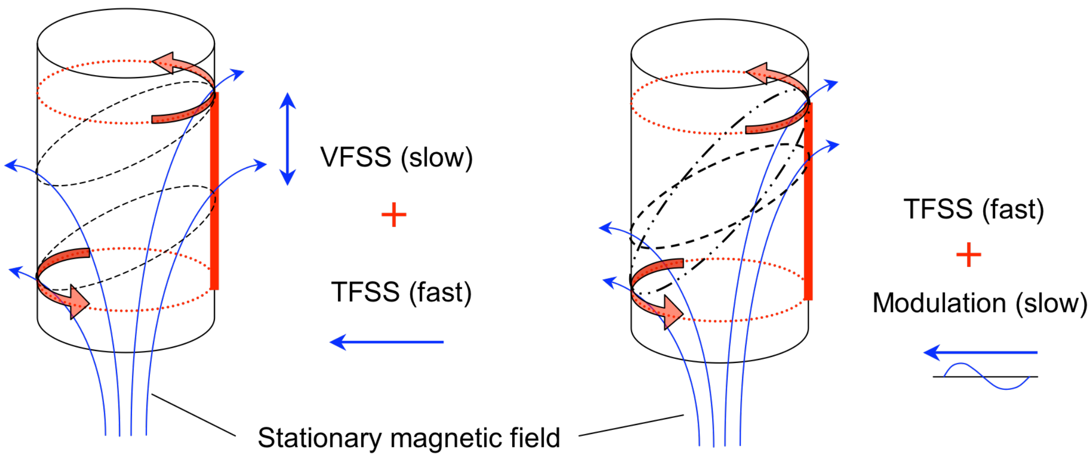

Fig.3: Principle sketch (snapshot) of a TFSS with vertical magnetic field modulation (left, method (a)) and with amplitude modulation (right, method (b)). The dotted rings mark the upper and lower turning points of the fast rotating tilted ellipses. The rotation is indicated by arrows.

The experiments were performed applying method (a) and using a commercial THALES Gyrotron TH 1507, SNo.3 (140 GHz, 1 MW, cw). The cylindrical collector is about 1 m long with a diameter of 0.5 m. The measurements are taken with an array of 49 thermocouples mounted at equal distances along the vertical direction of the collector. The temperature rise is measured as a function of vertical distance for the optimum sweep parameters. The Gyrotron set-up with the VFSS and the TFSS is shown in Fig. 4. The TFSS consists of 3 pairs of TF-coils, which are powered with a 3-phase AC-supply thus generating a transverse field, which rotates with 50 Hz (for details see ref [5]). The beam spread (FWHM) without Sweeping is about 50 mm in the vertical dimension leading to a power density at nominal operation of about 20 MW/m2, which is unacceptably high. The measurements were performed with reduced e-beam parameters (typically 0.75 MW, i.e. 15 A, 50 kV). For

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reference we have measured the power distribution with a commercial VFSS and the TFSS. The power deposition profile obtained with VFSS only displays pronounced maxima of almost equal height at both the upper and lower turning points (see Fig. 2). With the TFSS the upper maximum is reduced, the lower one, however, remains and no advantage is achieved with respect to the limits, which have to be set to collector operation.

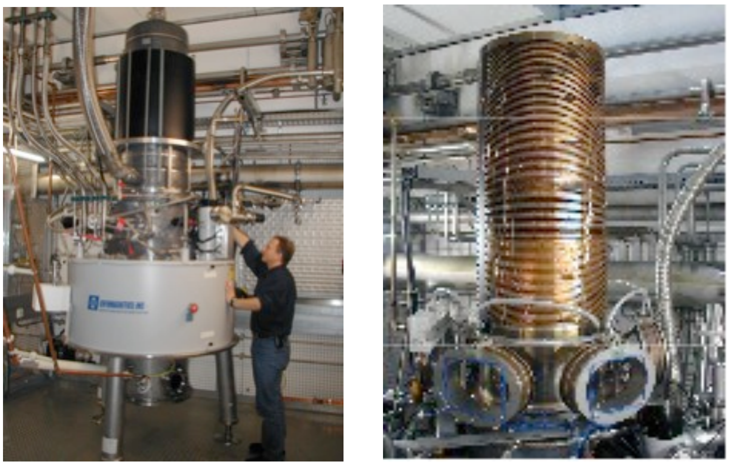

Fig. 4. Left: The THALES Gyrotron. The normal conducting VF-coil (black) surrounding the collector is seen at the top part of the gyrotron.
Right: The gyrotron collector with the three pairs of TF-coils installed (VF-coil removed).

The measurements with thermocouples were confirmed by thermographic imaging, were the temperature rise along the collector area was measured with a calibrated infrared camera. This method, however, applies only for TFSS experiments, because for VFSS- experiments the collector is covered by the large VF-coil with no access for infrared imaging. The results are well reproduced by numerical simulations.
For the advanced sweeping measurements we have adjusted the coil currents in both the VFSS and the TFSS to maintain the same overall beam spreading, i.e. with increasing TFSS, the VFSS has to be reduced and vice versa. Optimum profiles of the temperature increase are plotted in Fig. 5 together with the VFSS profiles for reference. The peak loading is reduced by almost a factor of two, thus enhancing the collector capability by the same amount. Here, an additional gain is achieved by fine-tuning with a small DC-magnetic field, which shifts the lower turning point slightly upward.

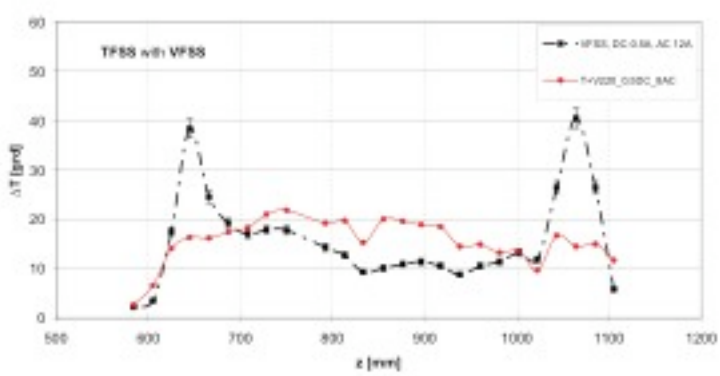

Fig.5: Profiles of the collector temperature increase ΔT along the vertical coordinate z for advanced sweeping: TFSS 3.5 A, VFSS 8 A, plus 0.5 A DC-current (dots). The profile for VFSS only is also shown for reference (squares).

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Summary

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Patent Information

Patents in Germany, France, United Kingdom, Russia, and USA
(priority date: January 16, 2008)

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Contact

Dr. Wolfgang Tröger

Senior Patent- & License Manager
Physicist

Phone: +49 (0)89 / 29 09 19 - 27
eMail: troeger@max-planck-innovation.de

Max-Planck-Innovation GmbH
Amalienstr. 33
80799 München
www.max-planck-innovation.de