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論文内容の要旨

Recently we observed strong spurious oscillations caused by the backstreaming electrons from the collector in the 324MHz 3MW 650ms klystrons developed at KEK. During the high-voltage processing of 324MHz klystron tube #1, unexpected oscillations were observed from both the output and input cavities when there was no driving input power. These oscillations occurred when the beam voltage was 63~71kV or higher than 90kV, and had frequencies close to 324MHz. After some investigations, the oscillations were identified to be the results of the backstreaming electrons from the collector. The collector size was accordingly changed to evaluate its effect on the backstreaming electrons. The experiment results of klystron tube #1A and #2 with modified collector of increased radius and length, indicated that the oscillations disappeared in the low beam-voltage region, and started from 95kV and higher than 104kV respectively.

In order to understand the oscillations and to improve the klystron tubes, this thesis has studied on these spurious oscillations due to the backstreaming electrons from the collector. These electrons originally come from the backscattering of the electron beam on the collector surface. According to the course of the oscillations, the study covers three parts: the production of the backscattered electrons on the collector surface, the formation of the backstreaming electrons into the drift tube, and the oscillation mechanism due to the interaction between the electrons and rf fields.

At first, the electron backscattering process has been investigated and simulated using the EGS4 Monte Carlo method. Electrons emitted from a bombarded material-surface are generally divided into two classes: the true secondary electrons whose energies are less than approximately 50eV, and the backscattered primary electrons whose energies vary continuously from the primary electron energy to lower energies. In this thesis, we concern those backscattered electrons that have high energies corresponding to the klystron applied-voltage from a few keV to several hundred keV. These backscattered electrons have been calculated by an EGS4 user code. The electron backscattering coefficients and energy distributions have been obtained under different conditions of incident energy and angle. For example, for normal incidence on copper, the backscattering coefficient is equal to 0.3, and it increases with the incident angle. The trajectories of the backscattered electrons are also plotted out by a FORTRAN90 program. The EGS4 simulation results agree well with the experimental data of the reflected electrons.

After the above confirmation of the EGS4 code validity for the fundamental process, the simulations of the backstreaming electrons from klystron collector have been performed by the EGS4 code. The simulation method includes three steps. (1) The trajectory calculation for the incident beam in the collector up to the collector wall. This step is performed by a FORTRAN90 program. Besides the space-charge forces, relativistic effects, self-magnetic fields and external magnetic field effects are included in this calculation. The calculation results have shown a good agreement with the EGUN95 simulation results. (2) The simulation of the electron backscattering in the collector using the EGS4 Monte Carlo method. This step is performed by an EGS4 user code, which processes the initial conditions, collector geometry, electron motion in the magnetic fields, and output of the backscattered and backstreaming electrons. (3) The post-process for the backscattered and backstreaming electrons. This step includes two FORTRAN90 programs; one is for the electron trajectory plotting, and the other is for the calculation of the z-component energy distribution of the backstreaming electrons. Some simulation results are also given in this thesis. The backstreaming electron coefficients and energy distributions have been obtained under different conditions of the klystron. The simulation results indicate that the backstreaming electrons are essentially independent of the beam voltage. For klystron #1, #1A, and #2, the backstreaming electron coefficients are 0.66%, 0.17%, and 0.13%, respectively. The contributions to the backstreaming coefficients from the cylindrical surface and cone-shaped surface of the collector have also been investigated. The former contribution mainly comes from the backscattering of the beam edge, and the latter contribution increases with the collector length shortening due to the direct reflection. The backstreaming coefficients have been carried out as function of collector diameter and length. Also the backstreaming electrons as function of various materials are obtained. It is clarified that lower atomic-number material results in smaller backstreaming coefficient. Furthermore, the transmission of the backstreaming electrons in the drift tube is investigated. It is indicated that most of the backstreaming electrons can pass through the drift tube to the input cavity region under the focusing fields of the klystron.

Finally, the study of the oscillation mechanism and conditions due to the backtreaming electrons has been performed, and relevant calculations of the oscillation conditions have also been executed using the previous results of the backstreaming electrons. Since the backstreaming electrons modulated by the gap voltage of the output cavity can induce an rf signal in the input cavity, they result in a formation of a feedback loop inside the tube. From the feedback theory, if an input cavity voltage can be regenerated by the backstreaming electrons, the oscillations will occur. Thus the oscillation conditions can be expressed by the complex product of the klystron voltage-gain and feedback coefficient caused by the backstreaming electrons: (1) the amplitude of the product should be larger than unity, and (2) the phase of the product should be zero or integral times of 2p. The voltage gain of the klystron has been simulated by JPNDISK. Since we are interested in the beginning of the oscillations, which is in small-signal linear region, the ballistic theory has been applied to calculate the feedback coefficient due to the backstreaming electrons by a FORTRAN90 program. Based on the calculations of the oscillation conditions, the beam-voltage regions of the oscillations for the 324MHz klystrons have been worked out. For klystron #1, the beam-voltage regions are 65~70kV and higher than 79kV. For the collector of #1A and #2, the regions are higher than 100kV and 105kV, respectively. These results show a good agreement with the experiments. With these analyses and calculations, the oscillation mechanism including oscillation phenomena has been understood physically and numerically. Suitable collector dimensions are proposed for 324MHz klystron in order to suppress the oscillations due to backstreaming electrons completely. Furthermore, some discussions and directions for future investigation on the oscillations are presented.

論文の審査結果の要旨

本博士論文は、大型ハドロン計画（ＪＨＦ）における線形加速器の高周波加速源として、現在高エネルギー加速器研究機構（ＫＥＫ）で開発中である、新型クライストロン（３２４ＭＨｚ、３MW、６５０μｓ）に関するものである。試作一号機の高電圧調整中に予期しない寄生発振が観測され、いくつかの予備的実験の結果、クライストロンの電子ビームがコレクターで後方散乱されることによって生じる逆流電子ビームがその原因ではないかと推測されるに至った。方志高(Fang Zhigao)氏の研究はクライストロン内部で起こる逆流電子ビームによる寄生発振に関するもので、その原因とメカニズムをほぼ完璧に解明し、その結果に基づいて寄生発振を防止する対策を提案している。

本論文では、まず、クライストロンのコレクター表面での後方散乱電子の生成について調べ、次に、この後方散乱電子がクライストロンのドリフトチューブ内へ逆流する電子ビームとなることを述べ、最後に、逆流電子ビームがクライストロンの入力、出力空洞と相互作用することにより正帰還ループが形成され寄生共振を引き起こすことを突止めている。

逆流電子ビームの生成については３段階にわたってシミュレーションを行い、その生成過程を解析している。まず、入射電子（正常なクライストロンの電子ビーム）がコレクター表面に到達するまでの軌道計算を空間電荷効果、相対論効果、自己及び外部磁場効果を考慮して行う。次に、コレクター表面で起こる後方散乱についてＥＧＳ４（モンテカルロ法計算機コード）を用いて、後方散乱電子の生成係数、エネルギー分布を求める。最後に、後方散乱電子の軌道計算を行い、それらが逆流電子ビームとなってドリフトチューブを逆流するアクセプタンス、および逆流電子ビームのエネルギー分布を計算するというものである。

寄生発振については、上記の逆流電子ビームの解析結果をもとにそのメカニズムを解明している。発振は逆流電子ビームが出力空洞の電圧で変調される結果、入力空洞にｒｆ電圧を発生させ、ある条件下でクライストロン内に正帰還ループが形成されることが原因と考えられる。そこで、正確なクライストロンの利得計算をおこない、さらに新たに計算コードを作成し正帰還ループの解析を行っている。製作されている３台の構造の違う試作機について上記の解析を行った結果では、寄生発振が生じるクライストロンの動作条件を極めて良く再現しおり、研究の精緻さが明らかに見て取れる。また寄生発振を防止するためのコレクターの構造に関する提案は十分納得できるものである。

以上、本研究はクライストロンの寄生発振に関してその全容を物理的、定量的に解析した点で類例を見ないものであり、また実用的な観点からも必要不可欠な研究である。研究手法においても、正確、着実に進めており、本審査委員会は、本論文が博士論文として十分な水準にあり、また本専攻に相応しい内容を持つものであると判定した。