

Development of the Industrial Electron Accelerator Ridgetron

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Abstract

A compact RF electron accelerator, the Ridgetron, with a ridged cavity resonator has been developed for industrial irradiation. It is of a recirculating acceleration type and is intended to have an energy range of 0.5-10 MeV and a beam power of 1-25 kW. A prototype system with an energy of 2.5 MeV and a beam power of 6.5 kW was constructed to confirm the feasibility.

1 Introduction

Many electron accelerators have been widely used for industrial electron irradiation (curing, crosslinking of polymers, sterilization of medical disposables, preservation of food, etc.). Regardless of the acceleration energy, the accelerators to be installed in industrial facilities have to satisfy the requires of compact size, low running cost and stable operation. A DC electron accelerator with high beam power is stable technique, however, its acceleration energy is up to 5 MeV because of the discharge of an acceleration column.

We have developed a RF electron accelerator system with a ridged cavity resonator for high-energy industrial irradiation such as the sterilization of medical disposables. It is of a recirculating acceleration type and is the first example of an electron accelerator which incorporates the ridged cavity. Its power efficiency increases in proportion to a number of recirculating acceleration by the same cavity up to the final energy. Since an acceleration voltage per pass is chosen relatively low in the recirculating type of accelerator, the heat loss of the cavity can be kept small resulting in significant power savings and the cw mode operation is feasible. This accelerator system is named the Ridgetron. It is intended to accelerate electrons with an energy range of 0.5-10 MeV and a beam power of 1-25 kW. As the first step to confirm the feasibility, a prototype system with an acceleration energy of 2.5 MeV has been developed.

2 Acceleration scheme

The Ridgetron consists of a cylindrical ridged cavity and small bending magnets at its periphery. The cross sectional view of the prototype machine is shown in Fig. 1. The

ridged cavity which is adopted as the acceleration cavity has the characteristics as the followings: (1) Its resonant frequency is lower than that of a same size cylindrical cavity without a ridged structure, (2) The electric field distribution can be optimized by varying the ridge shape, (3) The increase of an acceleration energy can be easily realized by using an axially longer cavity. The operating frequency of the Ridgetron is in a VHF band to allow use of a gridded power tube for its RF system. Therefore it easily becomes feasible to realize large beam power by operating in cw mode.

The acceleration scheme of the Ridgetron has been already described in the previous paper [1], and is summarized briefly here. In the acceleration cavity, two hollow ridge electrodes are equipped in the axial direction. The electric field excited by the TE_{110} mode is concentrated in the gap between the two ridges. The beam modulated by RF voltage applied to the grid of the electron gun to synchronize with the acceleration phase of RF field is injected into the cavity. It is passed through the inside of the ridges and the acceleration gap in the radial direction and deflected with the bending magnet after each pass. By adjusting the deflecting field of an arbitrary magnet to be zero, it is possible to extract the beam below the final energy. The acceleration period is every half cycle of the operating frequency. The drift length at an interval of acceleration is extended in proportion to the electron velocity to keep the synchronism. The beam focusing is performed with the edge focusing of the bending magnets equipped with the active field clamp to compensate the effect of fringing field.

3 Prototype design

3.1 Main cavity

The design performance of the prototype system was chosen at an acceleration energy of 2.5 MeV and a beam power of 6.5 kW that are quarter of the industrial machine. The cavity size is defined by its fundamental resonant frequency. The cavity diameter was optimized by varying the gap size and the ridge shape in a frequency range of 100-200 MHz. Although cavity size becomes compact by use of high frequency, beam cannot pass through the inside of ridges of narrow width required to keep high quality factor

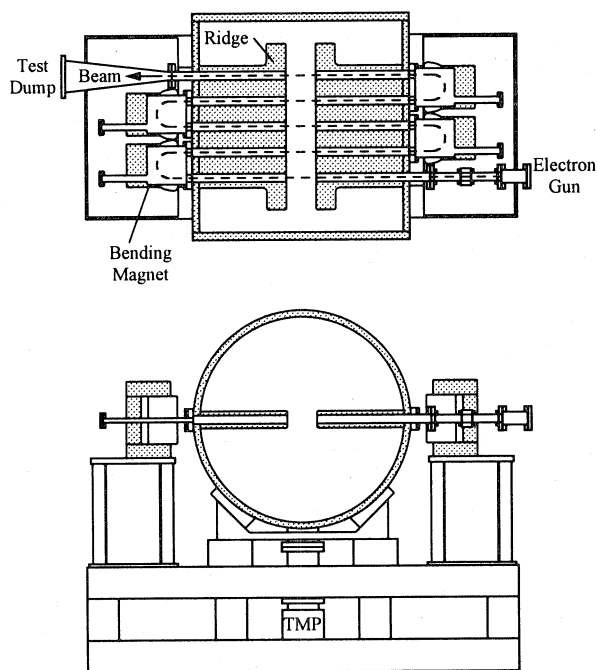


Fig. 1 The cross sectional view of the Ridgetron prototype

at the high resonant frequency. By choosing ridge width to give reasonable aperture for beam, the resonant frequency of 100 MHz was found to satisfy conditions of a compact size and low power consumption after optimization. Since the ridges function in the cavity as a capacity, the resonant frequency is 45 % lower than that of the same size cylindrical cavity without ridges. The electric field distribution was measured with a quarter scale cold model fabricated by using the calculated result. The overhangs of ridge ends have effects to improve uniformity of acceleration field along the ridge, so that the field drops at the first and final acceleration gaps are less than 5 %, compared to those at the central region of ridge. The cavity wall and the ridges are cooled by deionized water. RF power is fed into the cavity by inductive coupling with a loop coupler. The maximum output power of the amplifier is 60 kW. The specification of the prototype system is shown in Table 1.

The number of passes in the Ridgetron are limited by the cavity length and the deflecting radius of the bending magnet. Therefore small bending magnet with a deflecting radius of 65 mm was designed. The energy gain of the prototype is 0.5 MeV per pass to keep down the power consumption, so that the number of pass is five. Although the magnets are placed with space of only 20 mm between neighbors, each field is not disturbed as to affect beam trajectories.

Table 1 The specifications of the Ridgetron prototype

	Designed	Improved
Operating frequency	100	92.8 [MHz]
Input energy	20	20 [keV]
Output energy	2.5	2.5 [MeV]
Beam power	6.5	7.0 [kW]
Maximum gap voltage	0.5	0.5 [MV]
Cavity inner diameter	966	966 [mm]
Cavity inner length	990	990 [mm]
Gap length	140	140 [mm]
Ridge width	80	80 [mm]
Quality factor	27000	21000
RF ohmic power loss	42	50 [kW]

3.2 Electron gun

The prototype system must accelerate an averaged current of 2.5 mA to satisfy the designed beam power. Therefore the electron gun has to produce a peak current of 20 mA or more when the longitudinal beam acceptance is taking into account. A thermionic electron gun with the cathode made of a single crystal of LaB₆ was manufactured. The electrode configuration was optimized with the computer code EGUN2e and the flat type of Whentel electrode was adopted. It can operate in both of cw mode and pulse mode by change of modulation mode of the grid electrode voltage. The beam current measured at the bench test was 30 mA.

3.3 Beam focusing

The beam focusing of the Ridgetron is performed with an edge focusing and an active field clamp of the bending magnets. A magnet with a gap in its pole necessarily has fringing field, which reduces the focusing in the vertical plane. This effect is enhanced in proportion to the ratio of gap length and deflecting radius of the magnet [2]. Therefore the active field clamp which consists of a clamp iron and a sub-coil to excite an inverse field was developed [1]. It appropriately compensates a fringing field by adjusting the exciting current of the sub-coil. The results were verified with the computer code Power Trace which simulates a beam envelope including a space charge effect. In the calculation, the magnetic field region of the bending magnet with fringing field was separated into 17 segments and the field inside each segment was assumed uniform. The beam trajectory at the bending magnet is deflected more than 180 degrees because of use of the inverse field partly, where beam is deflected in reversed direction. By the scheme, a good focusing effect was obtained with the modest edge angle. The calculated beam envelope is less than ± 10 mm throughout acceleration trajectory.

4 Prototype experiment

The prototype system was constructed at Toshiba Corporation. Fig. 2 shows the view of the experimental setup. The first resonant frequency was 101 MHz and the measured quality factor was 23300. The electric field distribution measured by perturbation method was in good agreement with that of the calculated field.

The acceleration test with a low current beam has been carried out by using the first acceleration gap in the pulse mode operation. The beam profile was measured by fluorescence of ZnS(Ag) targets placed at the straight duct attached to the bending magnets. As a result, it was observed that the accelerated beam was deviated by the effect of RF magnetic field. Therefore the prototype was improved by equipping the ridges with metal blocks to minimize RF magnetic field in the acceleration gap. The improved resonant frequency is 92.8 MHz and the quality factor is 21000.

The cavity and the beam chamber of the bending magnets are evacuated with a turbo molecular pump to keep the vacuum pressure of 10^{-5} Pa in normal operation. The electron gun and the acceleration cavity are separable by a gate valve and an ion pump is provided for the electron gun to secure high vacuum.

5 Conclusion

A cw electron accelerator with a ridged cavity has been developed for industrial irradiation. As the first step, the prototype system was constructed. The electrical property is in good agreement with the design value. The beam test up to the final energy has been prepared at present.

References

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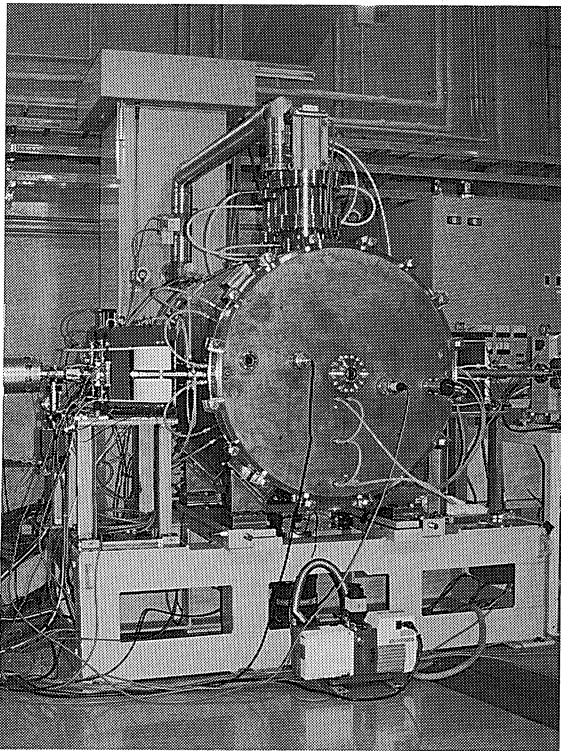


Fig. 2 The experimental setup of the Ridgetron prototype