RHODOTRON ACCELERATORS FOR INDUSTRIAL ELECTRON-BEAM PROCESSING : A PROGRESS REPORT

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1. INTRODUCTION

Rhodotrons are electron accelerators based on the principle of "re-circulating" a beam through successive diameters of a single coaxial cavity resonating in metric waves. Such design makes it possible to achieve CW acceleration of electron beams to high energies. The original design principle of the Rhodotron was first proposed in 1989 by J. Pottier from the French Atomic Energy Agency (CEA), who suggested the use of a half-wavelength coaxial cavity, shorted at both ends to accelerate electrons. The principle of operation of the Rhodotron has already been described in length in previous articles (1,2,3,4,5,6).

The first industrial Rhodotron (referred as model TT-200) was built in 1993 at IBA Belgium. It exceeded its expected performances in 1994 with a maximum beam output power of 110 kW at 10 MeV (100 kW expected), and a high power efficiency of 38 % at full beam power (25% expected).

Three industrial Rhodotron systems ranging from 35 kW to 200 kW beam power at 10 MeV have been completely designed, and are routinely manufactured at IBA's facilities in Louvain-la-Neuve. Specifications of these industrial accelerators were chosen in order to address the needs of the market of industrial irradiation for simple, compact and reliable high-power EB units:

Model	**Energy** *(MeV)*	**Max.Power** *(kW)*	**Size (∅)** *(meter)*
TT100	3 - 10	40	1.6
TT200	3 - 10	100	2.9
TT300	3 - 10	200	2.9

2. RHODOTRON TECHNOLOGY

2.1 Operating Principle

Rhodotron cavities are shaped as a coaxial lines shorted at both ends and resonating in the $\lambda/2$ mode at 107.5 MHz or 215 MHz. The beam crosses the cavity in the median plane through successive diameters (see figure 1). External window-frame magnets are used to bend back the electrons emerging from the cavity and to redirect them toward the cavity centre.

A high power RF system using a tetrode produces the electric field allowing an energy gain of 0.833 or 1 MeV per crossing. Ten or twelve crossings of the cavity (which means nine or eleven bending magnets) are therefore required to obtain 10 MeV electron beams.

As a result of the optimization procedure, IBA's technological option is to use commercially available RF power tubes operating at a frequency of 107.5 MHz for the Rhodotrons TT200 and TT300, and at 215 MHz for the smaller unit "TT100".

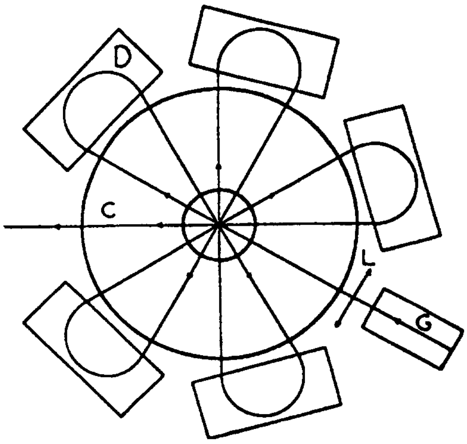

Figure 1: Median section of the accelerator and electron trajectory (D: deflecting magnet, C: accelerating cavity, L: magnetic lens, G: electron gun)

2.2 Accelerating cavity

The cavity diameters of both the TT200 and TT300 is 2 meter. In these conditions, energy gain is 1 MeV per crossing. In these Rhodotron models, five and ten successive crossings are therefore needed to obtain respectively 5 and 10 MeV at the exit of the Rhodotron.

A smaller cavity (diameter of 1 meter) was selected for the TT100 Rhodotron (10 MeV / 35 kW guaranteed power) in order have a very compact design. Energy gain of the TT100 is 833 keV per crossing. Therefore, 12 passes are necessary to reach 10 MeV at the exit of this accelerator.

Cavities of Rhodotrons TT200 and TT300 are made out of rolled, shaped and welded plates of steel. After machining the inside, the flanges and the other reference surfaces, the cavities are electrochemically copper-plated.

This copper-plating process results in a Q factor close to 40.000 and the power required to produce the electrical field allowing the energy gain of 1 MeV into the cavity is about 75 kW. The smaller "TT100" Rhodotron uses a cavity made of copper (5 mm thick), electron welded.

2.3 Electron Gun

The electron gun is located at the outer wall of the accelerating cavity. In order to match the RF frequency (the electrons have to be injected into the cavity when the field is accelerating), the gun is pulsed at the RF frequency and thepulse width is equal to 60° of the RF period. Electrons are injected into the cavity at a voltage of about 35 - 40 kV.

The design uses a commercial set of grid-cathode assembly from a commercial planar triode manufactured by Varian. The use of the grid allows to modulate the emitted current.

2.4 RF System

The RF system consists of a voltage controlled oscillator followed by a chain of amplifiers. Amplification stages up to 200 W are made of solid state devices. The two final stages use tetrode vacuum tubes. The high power RF stage of both Rhodotrons TT200 and TT300 has been placed above the cavity, partially inside the inner conductor. The anode cavity and the accelerating cavity are therefore directly connected by a short 1/4 resonant inductive loop, eliminating the need for a pressurized wave guide. This coupling does not only contribute to the compactness of the Rhodotron but also provides a constant ratio between the cavity field and the RF voltage on the final tube anode. By this method, the variable beam loading shows up as a variable load resistance on the final tube, and the final tube operates always at peak efficiency.

This final amplifier uses a cathode-driven tetrode able to achieve a gain of 16 dB. This configuration operates in AB class with a low polarisation current, which is a good compromise between gain and efficiency. Moreover, there is no need for neutralization adjustment, which is usually critical. The low-ripple anode power uses a "12-pulse" rectifier. The tube as well as the blocking capacitors are protected with a solid-state (Thyristors) crowbar system.

The RF field amplitude of the Rhodotrons is maintained constant in the high quality factor cavity by a double feed-back loop. In the first loop, the voltage controlled oscillator is phase-locked to the cavity resonance frequency value.

The second loop regulates the injected power in the cavity at the accelerating field amplitude value.

2.5 Deflection Magnets

The role of the deflection magnets is multiple: first, they are needed to send the electrons back into the cavity after each diameter crossing in order for them to undergo another accelerating cycle. The magnets also contribute to the focusing of the beam. Moreover, their position can be slightly adjusted during the tuning of the machine, so as to fine tune the phase between the beam and the accelerating field.

Coils of the deflection magnets are split into two symmetrical parts, around the yoke. The lateral return yoke and the coils are rotated at an angle of 9°. This makes it possible to position a straight beam exit at each port, i.e. at energies of 1 to 10 MeV, in steps of 1 MeV. This configuration allows to get a constant magnetic field along the orbit of the electrons.

2.6 Control System

As a standard feature for all IBA machines, the Rhodotron control system is based on an industrial programmable logic controller (PLC). It includes all software required for the completely automatic operation, maintenance and troubleshooting of the accelerator. The control system is user-oriented. The user interface consists of a multi-window application, running on a IBM compatible PC. The system is menu driven through self-explanatory, color graphic displays representing essential aspects of the Rhodotron's operation.

2.7 Beam Delivery Systems

Standard beam delivery system of Rhodotrons include a 90° vertical bending magnet, a scanning magnet at 100 Hz allowing the beam to be scanned across a 1 meter wide band, and optical lenses or quadrupoles as needed for proper beam transport efficiency.

A beam delivery horn with a metal vacuum-to-atmosphere window is also part of the standard supply. The beam delivery system can be connected either to the 5 MeV or to the 10 MeV output.

A new beam scanning system was recently developed by IBA, which allows installation of the accelerator and of the conveyor system on the same level. This horn scans the beam before bending it in the direction of the products. Contrary to conventional systems, the new design insures that all electrons reach the product under the same angle. Such innovative horn will be installed at customer's site by the end of 1996.

3. INDUSTRIAL RHODOTRONS

Rhodotron **TT100** (10MeV/35kW guaranteed power) is an extremely compact accelerator (cavity diameter: 1 meter) convenient for medium capacity irradiation facilities, or for in-house integration in existing manufacturing processes (sterilization of medical products, food ionization, etc.).

The **TT200** (10MeV/80kW guaranteed power) is convenient for industrial applications where high dose or/and high irradiation throughputs are required. The total height of the accelerator is 2.2 meters, including the RF power amplifier placed on the top of the cavity.

The **TT300** (10MeV/150 kW guaranteed power) is convenient for very high throughput / high dose applications (in particular for cross-linking of polymers). Overall power efficiency of this unit is about 49 % at maximum beam power (200kW), including power supply of accelerator subsystems (vacuum, primary cooling, control system, etc.).

4. RECENT PROGRESS

Presently, six industrial Rhodotron systems have been sold in Europe and United States, including one or several units of each model. Most of these accelerator systems will be delivered at customer's sites by the end of 1996, or in 1997. A TT300 system (10 MeV/200 kW) was recently installed at Studer A.G., Switzerland, a private company offering multi-purpose irradiation services. The whole accelerator operates since April 15, 1996. Acceptance tests of this Rhodotron will be performed by the end of June 96, when all facility subsystems will be in operation. This accelerator and related beam delivery system (including a 1 meter length scan horn) have already demonstrated the following technical performances :

- up to 185 kW beam power;
- operation of the Rhodotron above 100 kW beam power during more than 300 hours;
- high stability of beam current: less than 0.2% drift within several hours of operation;
- excellent beam current control: about 25 µA accuracy;
- excellent scan uniformity: better than 95% uniformity over 90% of nominal scan length. This is because energy spectrum of Rhodotrons is very tight. Moreover, there is no limitation is scan frequency since Rhodotron beams are C.W. (Continuous Wave), not pulsed as linacs.

Validation tests and industrial irradiations are currently performed by the customer at the rate of about 1 day per week, with various industrial products. Start-up operation of this accelerator has been performed rapidly since the whole accelerator system had been set up and tested at IBA factory in Belgium.

The present limitation at 185 kW has been detected to be due to the electron gun only (max. 18.5 mA). Upgrade of the cathode-grid assembly is under study to further increase the maximum power output.

A TT200 Rhodotron system (10MeV/80kW) has been recently delivered to the United States where will be operated by the end of this year within a contract service centre (the building is still under construction). This accelerator has already been operated during more than 6 months at IBA factory in Belgium where it confirmed the many advantages of Rhodotrons compared to other technologies: a CW (continuous wave) operation mode, a high power efficiency (total consumption was 265 kW at 100kW beam power), easy cooling of the accelerating cavity and high insensitivity to temperature variation, minimized maintenance, and a simple design inducing an intrinsic reliability. It must also be pointed out that the Rhodotrons are not "pushed" to their technical limits, and future power upgrade is possible for all available models.

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