# PRACTICAL ADVANTAGES OF THE RHODOTRON®

From its very beginnings, the Rhodotron® electron beam accelerator was designed to be an industrial tool, to be used in industrial settings, and to demonstrate a reliability, flexibility, and operational economy that could meet and surpass the most strenuous of industrial demands. Using an elegantly simple design, the Rhodotron® meets its design objectives, and offers the world a truly unique departure from yesterday's technology and limitations. From its low per kW cost to its built-in maintenance monitoring features, every aspect of the Rhodotron® and its subsystems demonstrates unfaltering attention to practical efficiencies, ease of use, and operational superiority.

The practical advantages discussed in this article focus on the accelerator's performance and features as they would be viewed in the eyes of a seasoned accelerator user and the facility's management. Of key interest are features such as electrical efficiency, ease and speed of maintenance, overall reliability, and flexibility in terms of matching capacity to production demands. Whether for use in sterilization, polymer modification, pulp processing, cold pasteurization of food, or basic research, these practical advantages cannot be overlooked.

## RESERVE POWER AND ECONOMY

Operating in a continuous wave (CW) mode and with three basic models to choose from, the Rhodotron®'s guaranteed ratings for beam power at 10 MeV are not only conservative but represent the widest demonstrated range available in today's industrial processing market.

The smallest Rhodotron® currently available is the model TT100, with a guaranteed power up to 40 kW. The intermediate unit, the TT200 has a guaranteed power up to 80 kW. The model TT300 ranges from 40 to 420 kW. All three models have been built and shipped to customers throughout the world.

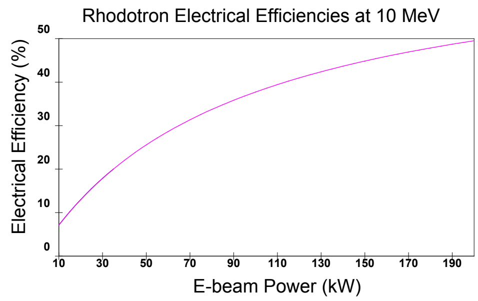
On the high powered end with up to 420 kW of beam power, the Rhodotron® model TT300 is several times more powerful than any other 10 MeV electron beam in operation today, yet in terms of capital cost per kW of beam capacity, it is less than a third that of other technology sold. Additionally, even at 200 kW, it will operate with no more electrical power consumption than its linac counterpart at 50 kW.

For lower power applications like in-house sterilization, the model TT100 is a scaled down version of the original Rhodotron®, with a smaller footprint and price tag to match. Even when the full 40kW of beam capacity is not used, it remains extremely competitive in all aspects of economy….even when compared to units of less than half its kW rating! Moreover, this increased reserve of capacity means that short-sighted purchases can be avoided, and an in-house operation needing only 15 kW today will not need to repurchase in 5 or 10 years time when their production doubles.

## ELECTRICAL EFFICIENCY

Operating at 10 MeV with 40, 80, or 420 kW of beam power, the Rhodotron® models TT100, TT200, and TT300 have "wall-plug to beam power" electrical efficiencies of better than 20%, 31%, and 43% respectively (guaranteed). At 100 kW and 200kW of beam power, the TT200 and TT300 will perform at efficiencies close to 36% and 50% respectively. Even greater efficiencies are obtainable at lower MeVs.

These quoted and guaranteed efficiency values are proven (not theoretical) and inclusive of all accelerator components, power supplies, electronics and control cabinets, primary cooling loops, etc. (basically everything except the secondary cooling system which is not included in the standard IBA scope of supply anyway). When similar holistic values are compared with equivalent units of the same voltage, the Rhodotron® is consistently 2 to 4 times more efficient. Depending on the size of unit required and local electricity rates, these exceptional efficiency values can result in hundreds of thousands of dollars in electricity savings per year (in both peak demand and power charges).




*Compared with other accelerators, the Rhodotron® is two to four times more efficient.*

## NO KLYSTRON

Because the Rhodotron® operates in a continuous wave (CW) mode, it does not need a klystron to amplify the accelerating RF signal. Instead, it uses a cathode driven tetrode which, by design, always operates at peak efficiency.

Under normal operating conditions, the Rhodotron®'s tetrode may have a useful life span up to 4 times that of a klystron installed in a similarly rated linac unit. Moreover, when a tetrode change is required, the new component will be readily available (unlike some klystrons), cost as little as a third that of a new klystron, and depending on the accelerator's design, could require many hours less to replace since in the Rhodotron® such replacements do not require breaking the vacuum in the acceleration cavity. Combined, these direct and plant-time cost savings will add up dramatically over the service life of the unit.

## ELECTRON GUN USES A COMMON CATHODE- GRID ASSEMBLY

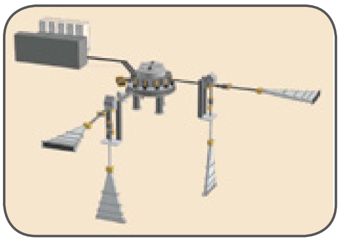
The Rhodotron®'s electron gun uses the same type of standard cathode and grid assembly that is commonly found in small UHF electron tubes (planar triodes). As such, it has been well tested and refined in industrial settings. It is low in maintenance and replacement cost, and abundant in supply when the time comes for it to be replaced.

## FLEXIBILITY IN BEAM VOLTAGE

Supplied as optional configurations, there are several ways in which the Rhodotron® can be configured so as to provide different beam voltages (MeV) from the same unit. The unit may be supplied with 2 beam lines and scan horns, each exiting at different ports of the accelerator cavity (eg. one 10 MeV exit operating in electron mode and a second one at 5 or 7 MeV in X-ray mode).

Within limits, such configuration modifications can be done with a conservation of total beam power (eg. 80 kW of beam at either 10 MeV and 8 mA or 8 MeV at 10 mA), and in some cases, reduction of the MeV at a given port can even increase overall power efficiency.

This degree of flexibility and power preservation is rare in most linac systems. It is however a boon to the Rhodotron® user, whom if faced with a product change requiring less penetration voltage, has the option to "capture" the gains of the lower voltage setting in the form of improved throughput opportunities (line speed is related to mA). Additionally, this feature enhances the resale value of the Rhodotron® (for example, when an owner is ready to purchase an even larger Rhodotron®) because it opens up a wider range of potential new owners for the system (i.e. not restricted to those needing just a 10 MeV machine).



*The Rhodotron® offers the possibility to have several beamlines at different energies.*

## EASY TO COOL

Possibly one of the greatest concerns for a high powered linac designer or operator is that of waveguide cooling and temperature regulation. This is because of the double edged sword that is inherent to linacs.

Linac waveguides are relatively small and have an extremely high power to surface area ratio (in the range of Megawatts/square meter during a pulse), which, when it comes to cooling, means that they operate at very high temperatures and require immense amounts of coolant flow. Inadequate cooling system design, air bubbles in the coolant, or faults in the primary or secondary cooling system, can all spell disaster for some types of linacs. Hot spots within the tube, sometimes developing within seconds, have been known to melt waveguides.

Another problem with conventional linacs and their cooling is that they must usually operate in a very narrow temperature range, often as small as plus or minus 0.5 degrees Celsius. This is because as the waveguide heats up, its metallic structure expands and this changes the resonant frequency of each small cavity. This results in mismatches and power reflections between the waveguide and the klystron.

Both of these problems are virtually eliminated with the Rhodotron®'s unique radial metric wavelength design. Instead of dissipating power (heating) over a small surface area, the interior wall surface area of the Rhodotron®'s accelerating cavity is several orders of magnitude larger than that of a linac. Heating is proportionately less severe, moreover, ordinary water is used as the coolant to the Rhodotron® structures.

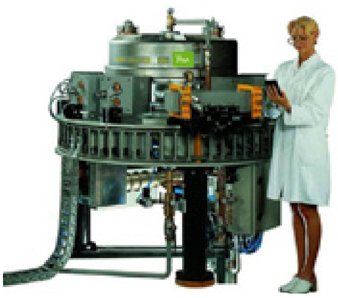
On the issue of heat regulation, the Rhodotron® can operate within a temperature window of about 5 degrees Celsius. This is because the frequency source

of the Rhodotron® is linked by an electronic circuit to the resonant frequency of the cavity. When the cavity expands due to temperature changes, the frequency source follows automatically to maintain perfect tune.

To the end user, this means that the Rhodotron® is a non-temperamental machine, and that its expected reliability (up-time availability) is significantly greater.

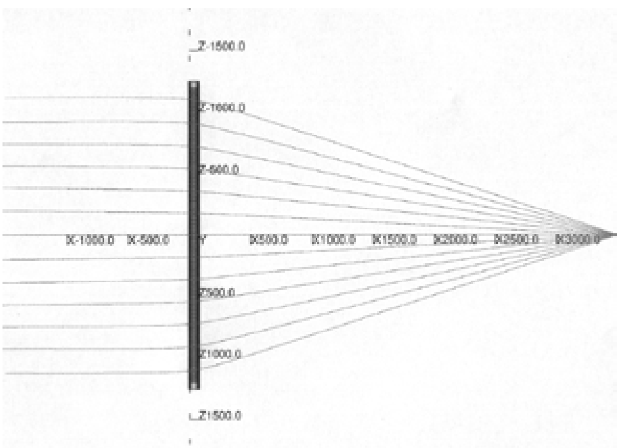
## COMPACT

With a model TT100 footprint of only 1.6 meters in diameter and a height of about 1.75 meters, the Rhodotron® is far and away the most compact electron beam accelerator in its class. Over and above lending itself to easy maintenance, the compact nature of the Rhodotron® serves to significantly reduce the amount of shielding required to house it. Compared to some accelerators of equal or lesser voltage and power, the petite size of the Rhodotron® can, in some plant configurations, reduce shielding expense by as much as 30% or more. Its low profile also lends itself to vault and building constraints where local codes limit building heights.



## NON DIVERGING BEAM OUTPUT

As an option, the Rhodotron® can be supplied with a two-staged scan horn system that delivers a scanned but non-diverging (parallel ray) beam. The first section of the scan assembly is a typical triangular-shaped scan horn which scans the beam spot back and forth in a uniform yet divergent pattern. At the window end of the scan horn is a second bending magnet assembly that reorients the electrons, so that the resultant beam is non-divergent.




*The Rhodotron® scan horn system provides excellent dose uniformity.*

This unique Rhodotron® scan horn option provides several major advantages in both the uniformity of dose delivery and the efficiency of beam utilization.

The non-divergent beam allows for a better fit between the top surface of the product to be processed and the path of the electrons passing near the edges of that surface. In conventional scanning systems there is an angle of incidence at the edge of the beam scan which is not at right angles to the treated surface. This means that the edge electrons are directed to clip through the corners of the treatment volume and deposit most of their energy outside of the product volume. In beam assemblies with wide solid angles, this can reduce the effective efficiency of beam utilization by as much as 15%. This waste is avoided using the Rhodotron®'s non-divergent scan system.

As a conventional beam diverges, the dose rate at further planes drops because the beam is spread out over a wider area. In some configurations, especially where the divergence angle is large or where the scan apex to product surface distance is small, this means that the surface dose can be greatly affected by small changes in distance to the window. Moreover, it means that at depths deep to the product surface, there is an added element forcing a wider max to min dose ratio. Again, both of these effects are minimized with the Rhodotron®'s non-divergent beam option.

Finally, with all the electrons coming towards the product in a pseudo-coherent pattern, the electrons hitting the product at the edges of the product volume are doing so in the same manner as they are in the center of the beam. This means that the "cosine effect" which is sometimes seen in product-beam configurations that optimize beam utilization will no longer be evident. As a result, tighter max/min dose ratios are expected.

## ASSYMETRICAL SCANNING

As an option, the Rhodotron® can be supplied with an adjustable off-set of the center of the scan. For certain facility configurations using a horizontal beam to irradiate products passing beside (not under) the beam, this is a major advantage. Likewise, for certain special applications in the vertical mode, the ability to shift the beam (combined with the standard feature of a variable scan width setting from 30 to 100%) is useful.

When processing horizontally, the base of the product carrier is usually fixed, and thus to treat products at that position on the carrier, the beam has to be scanned at the maximum setting. If the full height of the carrier is filled with product, this is fine, however, if the full height of the carrier is not used, then empty space has to be irradiated. By both reducing the scan setting, and then off-setting the center of the scan downwards, there is no need to waste beam in empty space.

## CW MEANS UNRESTRICTED SCAN FREQUENCY

Unlike most linac systems, the CW beam current of the Rhodotron® eliminates the restraint of a low scanning frequency (typically set at about 5 Hz for most linacs). The Rhodotron®'s beam is scanned back and forth at a minimum rate of 100 Hz or more (optionally at 200 Hz). This ability to scan at a higher frequency generates a more uniform distribution of dose over the width of the beam scan, and prohibits the possibility of getting a "zig-zag" or "zebra-stripes" dose pattern appearing on the product when it is treated to very low doses at low beam power and high conveyance speeds. Additionally the scanning signals of the Rhodotron® are specially modulated to provide very steep fall-offs at the beam edge, without the "horn artifacts" commonly seen in many other types of electron scanning systems.

## CW MEANS A WIDER CHOICE OF BEAM CURRENT

Conventional linacs regulate their beam current by modifying a combination of variables such as the peak beam current during a pulse, the rep rate (how many beam pulses are triggered each second), and the pulse width (how long the beam is on for each pulse). Linac rep rates are relatively limited (on the order of 1000 pulses per second, and usually much less), and for practical reasons, this limits the range of averaged beam current (hence dose rates) available to the system. In the case of obtaining very low doses (for example, in dose setting and auditing procedures), these restrictions often require special procedures and bypass steps.

With the CW of the Rhodotron®, there is no pulse rep rate or pulse width as seen with linacs. There is however an RF microstructure (always on for CW and only on during the pulse for linacs). By analogy then, the equivalent of "rep rate" is fixed at about 107.5 million Hz or 215 million Hz (for the TT200/300 and TT100 respectively). Furthermore while there is no RF equivalent of "pulse width" in CW terms, for each of the 215 million RF cycles per second, electrons are only introduced into the RF field during the peak a sixth of the cycle. The variable used to modify beam current is the bias on the electron gun grid, and this is easily and accurately regulated over a very wide range.

In operational terms, this means that setting the system for low dose exposures can be done quickly, simply, very accurately, and without interruptions to the main production flow. Resolution of beam current settings is over 1000 steps of the full beam current, and optionally over 2000 steps. Current adjustments and settings can therefore be made in the order of a few micro-amps.

## TIGHTER CONTROL OF BEAM REGULATIONS

Because it is operated in a CW mode without the need to match (synchronize) multiple trigger signals or worry about missed or mis-shaped pulses, the Rhodotron® is offered with a guaranteed, self-regulating beam current stability of less than 0.5%. In statistical process control terms, this means that there is considerably less uncertainty in the beam current compared to many linac systems (sometimes as high as 10%), and that tighter production tolerances can be set. Overall, this will mean less system fault interrupts in production, and both tighter and more consistent dosimetry results within and between production runs.

## PROPORTIONAL BEAM CONTROL

In routine production, absolute dose levels within the product are controlled by the ratio between the beam current and the process line speed. This method, known as "proportional beam control", allows for the same dosing to be performed over a wide range of beam current settings, by merely keeping the beam current to product speed ratio constant (e.g. running half speed at half current).

While the ability to have proportionate beam control is not unique to the Rhodotron®, there is, however, a very important difference with the proportional beam control provided by the Rhodotron®, all other linacs and most DC accelerators. Most proportional beam controls monitor the beam current and then adjust for fluctuations and/or ramp-time changes in the mA by increasing or decreasing the product conveyance speed. This is because the accelerator beam currents are typically very slow to move from one non-zero current setting to another.

In Rhodotron® technology, achieving and stabilizing beam current is done in the order of milliseconds, from any beam current setting to another, over the entire operating range. In practical terms, what this means is that in proportional control mode, it is the conveyance speed which is monitored and it is the fast to respond mA that is modified. With this much improved method of keeping the ratio of beam current and conveyance speed constant, the dynamics of production and the consistency of dosing is dramatically enhanced.
Optimum matching of sterilization line speed with production conditions remote to the sterilization unit

proper, translates to the ability to continuously monitor and “line balance” the entire production line, and to cost savings by generating and using only the beam power that is needed at any given point in time.

## NO MISSED PULSES

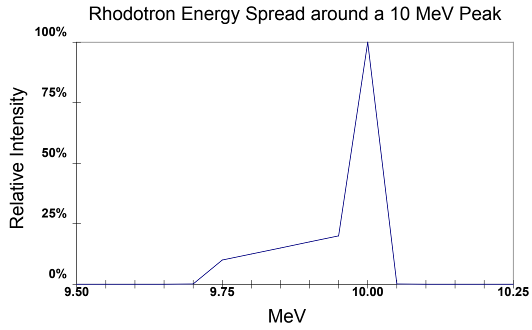
Basic linac designs require that the RF in the waveguide be intermittent (with proportionally long wait times between short “pulse-on times”) and perfectly synchronized with the timing of the electron gun.

If during this process, the synchronization between the on/off timing of the klystron and the release of electrons by the electron gun is not perfect, only a portion of the beam current is delivered during the pulse, or worse still, the entire pulse is missed by the electrons. Additional problems can arise if the pulse width of the klystron is not stable. If the particular linac system produces a significant number of missed or partially missed pulses, it will translate to uncertainties in the dose rate. If checks for this are not included in the linac’s design, it might lead to validation problems.

In the Rhodotron®’s CW design this is not a problem since the RF power is continuously present (there are no pulses) and electrons are continuously and evenly introduced into the system (about 215 million times a second in the TT100).
Also, there are continuous redundant measurements and comparisons of the current into and out of the accelerator cavity ensuring virtually perfect consistency both in beam current and beam voltage. Combined, these intrinsic design features of the Rhodotron® make the process of validation considerably easier and more complete.

## TIGHT MeV SPECTRUM

The energy spectrum around the set voltage of an accelerator is a tell-tale sign of the quality of the beam’s ability to deliver a tight max/min dose ratio with single sided irradiations. In many linac designs, there is a low voltage tail in the energy spectrum that serves only to increase the dose at or near the front surfaces of the product, but contributes little to the dose deeper within the product. While this is sometimes beneficial in two-sided irradiation, in one-sided irradiations it has a tendency to exaggerate the ratio between maximum dose found within the product unit and the surface or reference position dose.




*The Rhodotron® offers the tightest energy spread.*

The Rhodotron® has a designed energy spread tolerance of less than 300 keV at 10 MeV, and is in practice even tighter (as low as 100 keV). To IBA’s knowledge, this is the tightest MeV spread specification available without having to add a power wasting “beam scraper” to the electron path.

## INDUSTRIAL PLCs - FLEXIBLE, RELIABLE, AND EASY TO VALIDATE CONTROL SYSTEMS

The industrially proven programmable logic controller (PLC) used in the Rhodotron® is the same as those used in other IBA products undergoing FDA validations. Not supplied as a “black box” technology where the accelerator owner is not available to verify the logic codes or diagnostic inner workings of the control system, the Windows based control software is easily validated and immensely more flexible in terms of being able to add more feedback loops, more local and remote diagnostics, and more subsystem integration than most “in-house” developed control systems.

## SHORT WARM-UP AND RESTART CYCLES

Because many types of linac systems operate in a narrow temperature range, cold starts from prolonged weekend shutdowns (e.g. in standby) can for some systems require up to an hour or more of conditioning prior to full beam status. Likewise, after momentary interrupts (warm starts), the restart cycle may take as long as 15 minutes.

The wider temperature operating range of the Rhodotron® combined with its all solid state up-front signal generators and first stage amplifiers, shortens the cold start (standby) delay times to under 5 minutes, and likewise virtually eliminates delays for warm restarts. Ramp-up to full or selected beam power is nearly instantaneous, or if desired, can be programmed to follow a set ramping scheme or follow conveyor speed feedbacks during proportional beam control. The quick restart feature of the Rhodotron® can be extremely helpful in on-line production settings where more than momentary delays can throw off delicate production line balances.

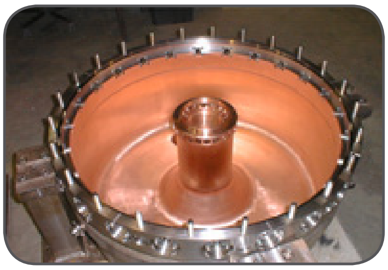
## MAINTENANCE IS EASIER TO TEACH AND MASTER

The elegantly simple working principle of the Rhodotron® has the added benefit of being easy to master in terms of routine and non-routine maintenance. Designed with a "plug and play" mentality in mind, troubleshooting and component replacements are quick and relatively non-complicated. Operationally pragmatic, this translates to overall cost savings since down times are briefer and in-house maintenance personnel need not be highly specialized (and often expensive) accelerator experts.

## EASY ACCESS TO ACCELERATING CAVITY

All DC and linac electron beam accelerators use a long, relatively narrow, and often multi-chambered accelerating cavity (waveguide) through which the electrons gain their speed and mass. In the event that the tube becomes contaminated or damaged, it is usually impossible to gain direct access to the inside of the tube to effect repairs. Sometimes, a contaminated waveguide will have to be replaced (at considerable expense and downtime) or else operated at lower voltage or power settings while the contaminant is "burned" out of the system. Damaged waveguides are typically not salvageable.

Such is not the case with the Rhodotron®. The accelerating cavity is, by comparison to other types of accelerators, huge and immediately accessible for decontamination or repair. In the rare event that a contaminant enters the system or repairs have to be made to the inside of the accelerating cavity (and the words "rare event" cannot be over-stressed here), the pill-box shaped accelerating cavity can be opened up at its mid-plane seam, and all inner wall surfaces are directly visible and approachable. An otherwise catastrophic event that could disable other types of accelerators for weeks or months, presents only a few hours of maintenance for the Rhodotron®.



*The accelerating cavity of the Rhodotron® is immediately accessible for maintenance.*

## BUILT IN PREVENTIVE MAINTENANCE SCHEDULING AND MONITORING

Using a graphically represented "point and click" Windows style look-up system, the Rhodotron®'s control system will display the status and operational condition of all key subsystems. Additionally, a time-line status is displayed for components subject to routine maintenance or replacement. This feature, which is part of IBA's holistic reliability approach, serves to better plan scheduled downtimes and to avoid production delays due to component failure.

## COMPONENTS ON OUTSIDE OF ASSEMBLY

Unlike many electron beam accelerators, the Rhodotron® was designed for fast and simple maintenance. All critical components are located outside of the accelerating cavity, and interfaced for rapid repair and/or exchange. This includes the electron gun assembly, the main tetrode amplifier, and all of the magnets used to redirect the beam in its rose shaped recrossings through the accelerating cavity. To ensure rapid start-ups after maintenance, shut-off valves and separate vacuum systems are used for the electron gun, scan-horn assembly, and accelerator cavity proper. From an operational vantage, this means shorter maintenance times and greater availability for production.

## NO SF6 GAS

SF6, an insulating or venting gas used in many electron beam accelerators is heavier than air, and is therefore OSHA classified as a suffocation hazard. The Rhodotron® does not use SF6, and instead uses dry nitrogen, a cheaper and non-hazardous venting gas.

## NO OIL TANKS

Since the Rhodotron® does not use a klystron, it eliminates the need for an oil filled "transformer tank" to be housed within the building. A potential fire hazard and often costly design and construction consideration (e.g. to provide a secondary oil spill and fire containment system), the absence of an oil tank in the Rhodotron® also translates to lower insurance costs.

## IBA EXPERIENCE AND EXPERTISE

The Rhodotron® is a new – hence proven - concept on the electron beam accelerator market. However, its manufacturer, IBA, is anything but an inexperienced newcomer. Very well known for its industrial, hospital and research cyclotrons (the Cyclone series), IBA has built a reputation for providing exactly what it promises with products of unparalleled reliability and durability. Currently manufacturing and marketing a wide line of diagnostic and therapy radiation products, including cyclotrons, automated chemistry systems for positron emission tomography (PET) users, and 230 MeV proton therapy units, the IBA team understands well what it means to design, manufacture, and deliver (over 120 accelerators so far). A simple phone call to anyone on the proudly offered customer/reference list will verify IBA's dedication to service and performance.

The Rhodotron® operating principle closely resembles the same technology of recirculating fields as is used in the IBA cyclone. Coupled with IBA's unsurpassed expertise in beam optics, the Rhodotron® is not a new technology for IBA but rather an extension of technologies that they have well mastered. Prospective customers should find comfort in IBA's proven track record of on-time delivery and machine performance.

## COMMITMENT

As of the printing date of this revision, IBA has sold no fewer than 16 Rhodotron units in companies around the world, and several more orders are expected soon.

While many of the practical advantages mentioned in this paper were influencing factors in the purchase decision process of our Rhodotron® customers, just as important was their confidence in IBA, its financial health and stability, its history of superior after sales service and support, and IBA's long term commitment to remain an active and leading force in the electron beam industry.

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## RHODOTRON PRODUCT RANGE AND SPECIFICATIONS

| | TT 100 | TT200 | TT300 | TT1000 |
|---|---|---|---|---|
| **Energy (MeV)** | 3-10 | 3-10 | 3-10 | 3-10 |
| **Max. Beam Power (kW)** | 40 | 80 | 420 | 560 (7 MeV) |
| **Full Diameter (m)** | 1.60 | 3.00 | 3.00 | 3.00 |
| **Full Height (m)** | 1.75 | 2.40 | 2.40 | 2.40 |
| **Weight (T)** | 2.5 | 11 | 11 | 11 |
| **MeV/Pass** | 0.833 | 1.0 | 1.0 | 1.0 |
| **Number of Passes** | 12 | 10 | 10 | 7 |
| **Primary Mode** | E-Beam | E-Beam | E-Beam/X-ray | X-ray |
| **Max Line Power (kW)** | <210 | <260 | <440 | <1300 (560kW) |