# WIDE BEAM ELECTRON ACCELERATORS FOR INDUSTRIAL APPLICATIONS

Sergey Korenev and Rolland P. Johnson

*Muons, Inc., 552 N. Batavia Avenue, Batavia, IL 60510*
*sergey@muonsinc.com*

*A conceptual design is presented of an electron accelerator for industrial radiation applications requiring a wide beam. Toroidal RF cavity accelerating structures are proposed to provide these wide beams, using either normal conductivity metal or High Temperature Super-conducting (HTS) films. The electron source design, design of the output foil window, beam energy, current regulation, and design of the x-ray target are considered. Manufacturing and operating costs are discussed.*

## I. INTRODUCTION

Radiation technologies based on electron beams and X-rays are found in a large number of industrial applications [1,2], including sterilization, polymerization, material modification, food irradiation, wastewater treatment, flue gas cleaning, and ozone generation. The typical structure of an industrial irradiator based on an electron accelerator is shown in Figure 1.

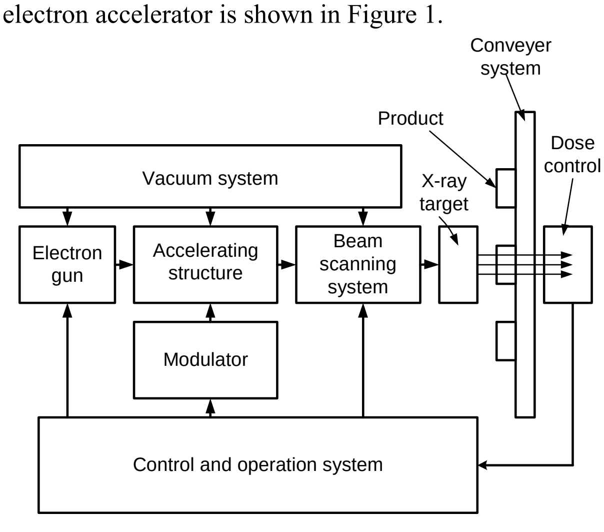


Fig. 1: General structure of an industrial irradiator based on a linear electron accelerator.

A critical analysis[3] of industrial electron accelerators has investigated their main problems and requirements. One problem is the implementation of the scanning electron beam that is normally used for irradiation of large products. One solution to this problem is to create a wide electron beam, a concept that we have previously suggested.[4]

Pulsed machine experience is primarily found in experimental laboratory environments rather than in industry. However, pulsed electron accelerators have the potential to have higher dose delivery efficiency than DC machines.[5]

These radiation technologies require new ideas, concepts, and approaches for electron accelerators for industrial applications. One new design concept considered in this paper is the use of High Temperature Superconductor (HTS) both for accelerating RF Cavities and for magnets for beam transport.

## II. THE WIDE BEAM CONCEPT

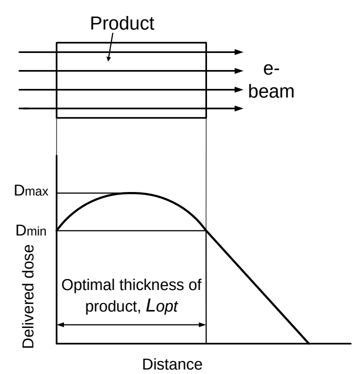


Fig. 2: The distribution of delivered dose from electron beam irradiation from one side.

The delivered absorbed dose $D$ in an irradiated product as depicted pictorially in Figure 2 is determined by the ratio of the deposited energy from the beam to the mass of the product:[6]

$$D = \frac{E}{m} = \frac{U \cdot I \cdot t \cdot K_1 \cdot K_2}{\rho \cdot L_{opt} \cdot a \cdot b} \frac{[J]}{[kg]} = [Gray], \qquad (1)$$

where: $E$ is the deposited beam energy, $m$ is the mass of the irradiated product, $U$ is the electron accelerating voltage (electron kinetic energy), $I$ is the electron beam current, $t$ is the irradiation time, $K_1$ is a beam dependent factor, $K_2$ is a time dependent factor, $\rho$ is the density of the irradiated product, $L_{opt}$ is the optimal thickness[7] from Figure 3, and $a$ and $b$ are the dimensions of the product.

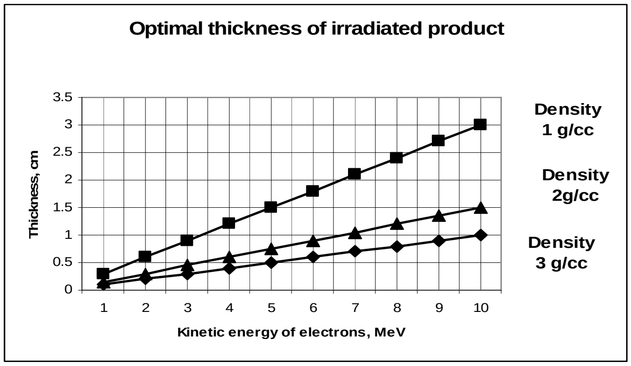


Fig. 3: The optimum thickness of a product irradiated by an electron beam as a function of electron beam energy for three different densities.

An analysis of equation (1) shows that to increase the delivered dose to the product it is necessary to increase the factors $K_1$ and $K_2$. The factor $K_1$ depends on the following factors:

$$K_1 = K_{Lopt} \cdot K_{angle} \approx 0.5 - 06, \qquad (2)$$

where $K_{Lopt}$ is factor relating the delivered dose with the average dose $D_{ave} = \dfrac{D_{\max} + D_{\min}}{2}$; $K_{angle}$ is a factor determined by the allowed variation of the delivered dose from the scanning electron beam, where the typical maximum scanning angle is $13^0$. $K_{angle} = 1$ for a Rhodotron[8] electron accelerator and for some transformer accelerators[9] with parallel scanning. The factor $K_2$ is determined by the scanning time of the beam, where $K_2$ is about 0.02 for scanning at 100 Hz with a beam length of 100 cm and diameter of about 10 cm. A larger beam cross section can increase $K_2$ and $K_1$. With a wide beam one does not need the scanning mode so that the factors $K_{angle}$ and $K_2$ can be increased to 1.

Equation (1) also shows that the current density is important. A typical realistic current density of 0.1 to 1 mA/cm$^2$ is used to deliver 25 kGy, which corresponds to medical sterilization of a product with 1g/cm$^3$ density for 1 sec. For 1 MeV kinetic energy electrons, the current density is about 10 μA/cm$^2$.

## III. WIDE BEAM ELECTRON ACCELERATOR

An analysis of DC electron accelerators and sources shows that a wide beam can be achieved using cold cathodes based on carbon fibers[10, 11] and high voltage vacuum insulation up to 5 MeV. Thermionic electron sources with low voltage (100-250 kV) have a large number of applications and there are good engineering designs[12]. The limitation of this type of electron accelerator is the large dimensions of the high voltage devices and low operating efficiency (wall plug power efficiency is about 30%).

The alternative accelerating structure that we will consider for production and accelerating of electron beams with large cross section is based on a toroidal RF cavity, indicated in Figure 4.

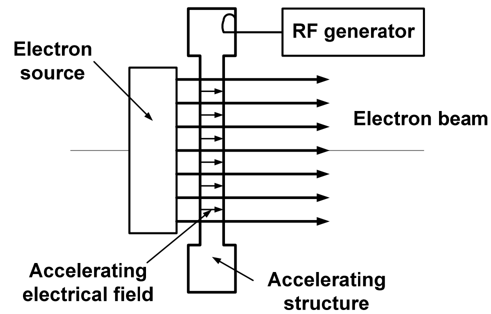


Fig. 4: Physical concept of an electron accelerator with wide beam using a toroidal cavity

The distribution of electrical and magnetic fields in the toroidal cavity is shown in Figure 5.

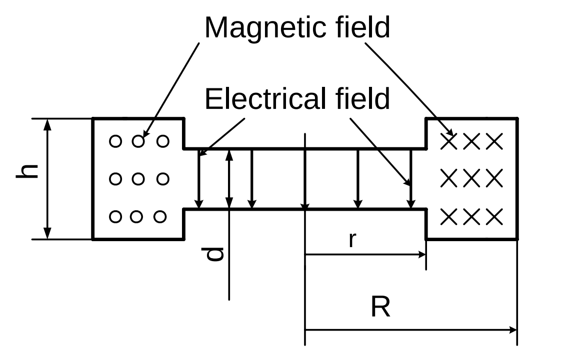


Fig. 5: Distribution of electrical and magnetic field in a toroidal cavity.

A toroidal cavity is electrically equivalent to an inductor and capacitor in parallel. The resonant frequency $f$ is determined by:[13]

$$f = \frac{1}{2\pi \cdot r} \cdot \sqrt{\frac{2d}{\varepsilon_0 \cdot \varepsilon \cdot \mu_0 \cdot \mu \cdot h \cdot \ln \dfrac{R}{r}}}, \qquad (3)$$

where $r$ is the inner radius, $R$ is the outer radius, $d$ is the distance between electrodes, $h$ is the width of the magnetic volume, $\mu$ is the relative permeability, $\mu_0$ is permeability of free space, $\varepsilon$ is the permittivity of the material, and $\varepsilon_0$ is the permittivity of free space.

The dependence of the toroidal cavity frequency on the accelerating gap, $d$, is shown on Figure 6.

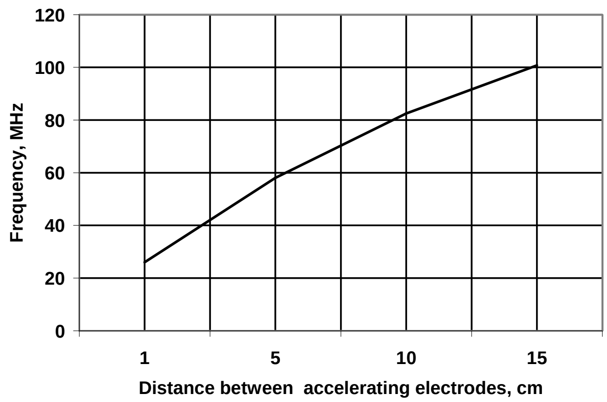


Fig. 6: The dependence of toroidal cavity frequency on the distance between accelerating electrodes for r = 50cm, R = 100cm, h= 40 cm.

Equation (3) indicates the toroidal cavity dimensions corresponding to industrial RF systems. The toroidal cavity is found to have dimensions similar to those of the Rhodotron[14] industrial accelerator.

The geometry of the toroidal cavity can be changed from cylindrical to rectangular in order to produce a rectangular electron beam.

## IV. ELECTRON SOURCE

Since the current density is low, only 5 to 100 $\mu A/cm^2$, cold cathodes with field emission can be used. The beam current can be controlled by varying the distance between the cathode and the anode according the Child-Langmuir law.

The electron beam has small perveance $P \sim 10^{-5}$ $\mu A/V^{3/2}$ compared to the critical value (0.1 $\mu A/V^{3/2}$). The effect of space charge on the size of the electron beam is very small [15].

Decreasing the beam cross section and increasing the perveance requires using magnetic fields to focus the beam.

Electron sources can be inside or outside of the accelerating structure.

### ***Electron source outside of toroidal cavity***

The electron source has a DC or RF power supply for extracting and accelerating electrons from the cathode. Carbon fiber is a good candidate for the cold cathode having a stable current yield [16], constant to about 0.4%. The emission properties of this cathode have been investigated [17]. A picture of this type of cathode is shown in Figure 7. The emission characteristics of carbon fiber cathodes are shown in Figure 8.

Fig. 7: Picture of ribbon cold emission cathode with carbon fiber**s.**

A field emission cathode can be made of HTS materials placed directly in the RF cavity. The generation of beam current from HTS cathodes has been investigated [18,19]. The main problem with HTS cathodes is a short lifetime due to surface morphology changes from melting.

Another potential cold cathode candidate is a Spindt cathode [20]. An electron source with surface discharge [21] plasma cathode is also acceptable for this application.

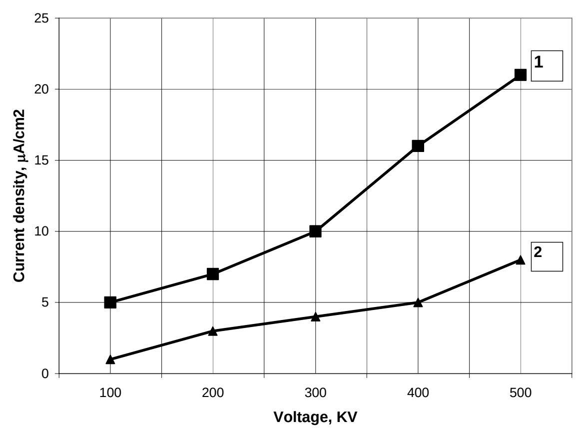


Fig. 8: Carbon fiber cathode emission characteristics for cathode and anode separations of 5 cm (1) and 10 cm (2).

### ***Electron source inside of toroidal cavity***

A toroidal cavity with fixed cold cathode on one electrode can serve as an electron source. The fabrication of the cold cathode requires the creation of a regular needle geometry using sputtering by nitrogen or argon ions [22].

## V. ACCELERATOR CONCEPTUAL DESIGN

The general conceptual design of the accelerator is shown in Figures 9 and 10. The accelerator consists of:

- electron source;
- accelerating structure with RF system;
- electron beam transition from vacuum to air;
- diagnostics;
- vacuum system;
- radiation safety shield;
- product transport system.

The main idea of this paper is the use of a toroidal cavity to accelerate wide electron beams. The materials for the toroidal cavity can be from normal conducting materials and/or superconducting materials.

However, an important new feature to enable a reliable, economical, and compact industrial electron accelerator is the use of modern technologies and new materials, such as HTS for RF accelerating structures and magnet focusing systems.

HTS for accelerating structures has been considered before [23], because traditional superconductors such as a Nb are not economically acceptable for industrial accelerators. The cost of liquid helium and cryogenic systems will be too high compared with traditional industrial electron accelerators in the range of 1to10 MeV and 1to100 kW. One advantage of HTS is that liquid nitrogen systems for cooling the cavity and magnets are less expensive to build and operate than liquid helium systems. Another advantage of HTS is a larger electric field gradient and quality factor for accelerating structures [24] compared with room temperature cavities. The toroidal cavity we propose for the conceptual design of an industrial electron accelerator for radiation technologies will have a thin layer or film of HTS material, which will operate at liquid nitrogen temperature.

HTS materials for a magnet system for this type of accelerator are realistic options with several advantages, including high radiation tolerance relative to low temperature superconductor [25]. The magnet system is necessary for high current applications with smaller beam sizes. For other cases, magnetic focusing is not required as in the case shown in Figure 11 which uses two toroidal accelerating structures.

Depending on requirements, the proposed electron accelerator parameters are:

- kinetic energy from 1 to 10 MeV;
- beam power either 5, 25, or 1000 kW;
- beam size:
    - Cylindrical, diameter 20-100 cm, or
    - Rectangular, (10 to 20) x (50 to 100) $cm^2$.

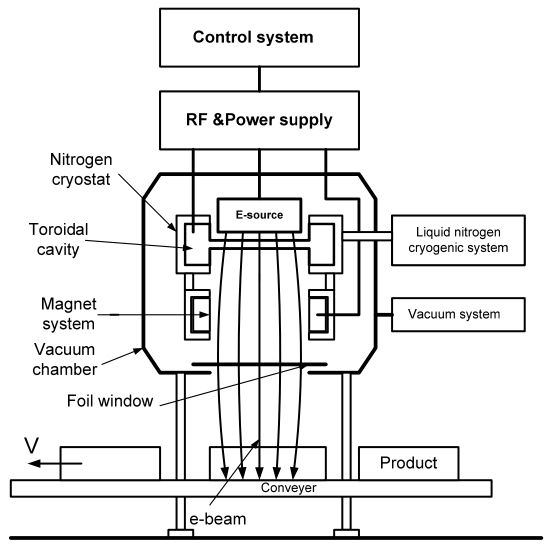


Fig. 9: Electron accelerator for radiation technologies with the electron source outside of the RF cavity.

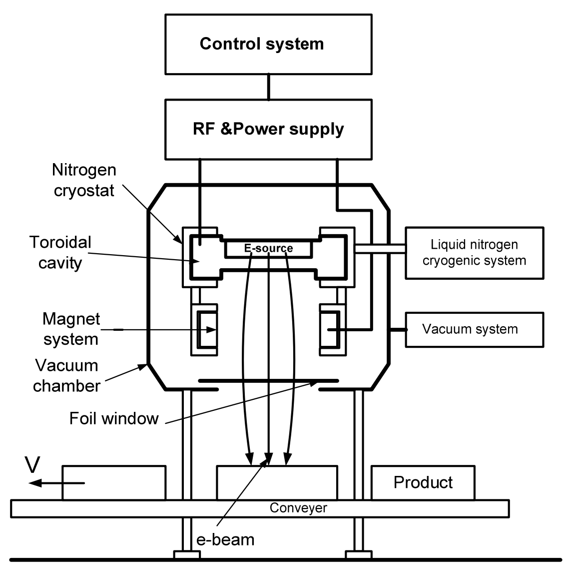


Fig. 10: Electron accelerator for radiation technologies with electron source inside of the RF cavity.

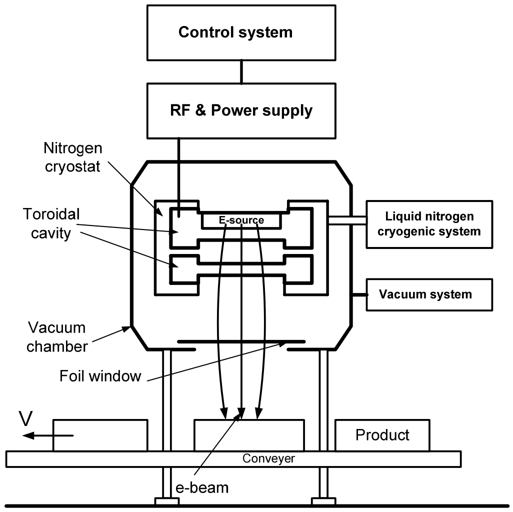


Fig. 11: Electron accelerator for radiation technologies with electron source inside cavity, two toroidal RF accelerating structures, and no magnetic focusing.

## VII. RF SYSTEM ACCELERATING STRUCTURE

The frequency of the RF accelerating structures follows from the dimensions of the desired electron beam. For a frequency range of 50 to 200 MHz, .traditional tetrodes and solid state RF generators can be used (e.g. Rhodotron [8]).

Toroidal cavities with normal conductivity can be designed with standard techniques. The design of RF cavities with thin HTS films is a new enterprise. The best candidate technique for fabricating superconducting cavities with thin film HTS is pulsed ion/electron adiabatic evaporation [26]. The physical principle of this method can be seen in Figure 12, showing the evaporation of anode material using a pulsed high power high voltage generator.

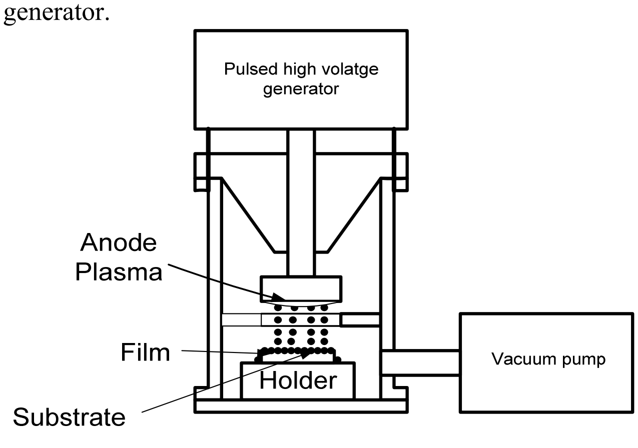


Fig. 12: Pulsed high voltage ion/electron film deposition.

The main advantages of this technology are:

- stable stoichiometric relationship of anode material and films.
- excellent adhesion of films to substrate.

This technology has been used successfully for HTS film deposition [27, 28] for large cross section toroidal cavities for experiments for electron beam compression and to form electron rings. Several potential HTS film candidates are possible, with the most likely at the present time being YBCO-1-2-3.

## VIII. FOIL PRESSURE WINDOW

The electron beam must pass through a thin foil pressure window that separates the accelerator vacuum (from $10^{-6}$ to $10^{-5}$ Torr) from the atmospheric pressure of the product transport area. The small beam current density reduces the thermal requirements of the foil. The thickness of the foil is determined by the kinetic energy of the electrons and losses in the foil. A metalized plastic foil with thickness between 50 and 250 μm can be used, while a more expensive beryllium foil may be needed for large electron beams, with thickness from 250 to 400 μm and dimensions 20 x 100 $cm^2$.

## IX. X-RAY GENERATION

The electron beam can be used to produce bremsstrahlung X-rays from a metallic target. The x-ray energy spectra can be limited by using a foil filter because the beam current and cooling requirements are low. The use of Mo, Ta, and Re on an Al substrate has been studied [29] as an X-ray target.

## X. ECONOMIC ASPECTS

The average capital costs of standard industrial irradiators based on electron accelerators are shown in Table 1.

Table 1.

| Type of accelerator | Accele-rator, $M | Rad. Shield, $M | Other, $M | Total, $M |
|---|---|---|---|---|
| DC | 5.0 | 2.0 | 1.0 | 8.0 |
| Linac | 5.0 | 1.0 | 1.0 | 7.0 |
| CW | 4.0 | 1.0 | 1.0 | 6.0 |
| Wide beam accelerator | 2.0 | 1.0 | 1.0 | 4.0 |

The wide beam accelerator considered here can be used to decrease the power for the same delivered dose by a factor of $K_2$ in equation (1). This improvement can be used to decrease irradiation time and/or the cost of electrical power.

The main revenue model discussed below is based on the radiation treatment for medical product sterilization on the basis of contract processing. In the following, the throughput is 10,000 lbs/hour or approximately 200,000 lbs/day, 1,400,000 lbs/week, or 70 million lbs/year.

***Annual Operation Cost:***

Staffing 4 full time equivalents * $40,000 per year per person = $160,000
Electricity $0.2 per kW-hr x20 kWx20 hrx350 days per year = $28,000.00
Subtotal $188,000.00
Contingency $37,600.00 (20% covers miscellaneous expenses)
Total first year $225,600.00

Service Contract $150,000 annual contract covering parts & Labor (after first year)

Total $375,600.00

***Annual Incremental Revenue:***

Contract sterilization companies are charging between 0.03 and 0.09 per lb (volume dependent). Assuming an average sterilization service price is 0.06 per lb:
70 million lbs per year x 0.06 per lb = $4,200.000 per year

Total Capital and Operation cost Years 1-2 (plus automated material handling)

| | |
|---|---|
| Purchase price | $4,000, 000 |
| Operation cost Yrs 1-2 | $751.200 |
| Total Cap& Op.Yrs 1-2 | $4,751,200 |
| Incremental Revenue Yrs 1-2 | $8,400.000 |
| **Profit** | **$3,648.800** |

This revenue model gives an approximate gross profit. A detailed consideration of product throughput for the optimum combination of electron accelerator/X-ray source parameters is needed to arrive at a correct profit estimate. Multiple beam lines, perhaps for different purposes and having different parameters, at one installation will save on infrastructure costs such as buildings and quality assurance.

## XI. CONCLUSIONS

The conceptual design of industrial electron accelerators with a wide beam using new materials for accelerating structures has been investigated. The benefits of this type of accelerator are:

- Decreased beam power for a delivered dose, and
- Increased radiation processing efficiency.


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