

# **ELECTRON-BEAM ACCELERATORS**

## **FOR NEW APPLICATIONS**

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## 1. FOREWORD

The purpose of this presentation is to give an overview of the current state of industrial electron beam development. It is not possible to present all of the technical details which one might wish because of the need to protect the proprietary interests of the firms engaged in the production applications and technology development. Still, the general view can be seen clearly.

## 2. INTRODUCTION

EB is the abbreviation for an environmentally safe, heat and solvent free technique: Electron-Beam curing.

The main driving force for the user to look at the EB technology is the desire to use an environmentally safe production method for Curing, Crosslinking and Sterilisation. Further reasons include:

- The EC Super directive regarding migration of less than 10 ppb into the food will force the packaging producer to look for new technologies. [28]
- Reduction of solvents or cracked products into the atmosphere and water.
- Full control of process parameters for the Polymerisation, Curing, Crosslinking and Sterilisation.
- Faster production.
- During and after the curing process there should be no emission of harmful substances into the atmosphere, water or into the food.
- After the curing process is over, there should be no odour emissions from the surface.

This has forced the equipment supplier to adapt and develop new types of Electron-Beam Accelerator to meet new demands like:

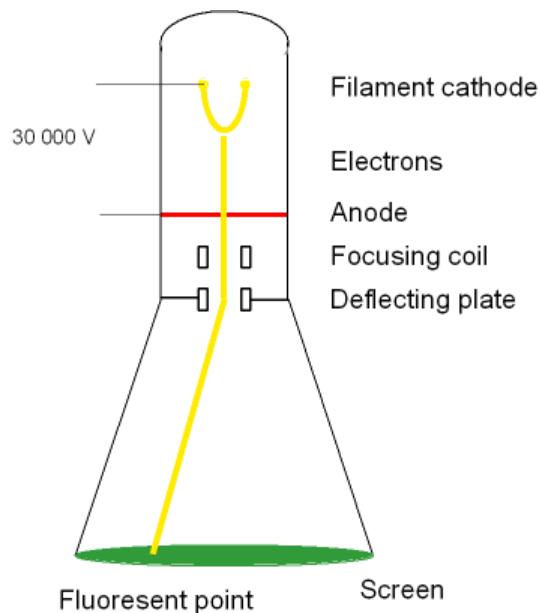
- Faster running equipment
- Smaller size
- Full control of curing parameters
- Traceability of process parameters
- New type of accelerators

Nevertheless, success is only possible if the user, the chemical supplier and the plant manufacturer collaborate fully – not only during the planning phase but also during the design of the curing line and later during initial operation.

## 3. THE ACCELERATOR

There are different types of accelerators available on the market, with different system designs and layouts. The common factor is that they all use high voltage to accelerate the electrons in vacuum. The electrons pass out of the vacuum into the air through a titanium foil stretched over a water-cooled support grid. The product treatment area is in front of the titanium foil. The large area window has a standard length in conveyor direction of 50 mm to 250 mm. The working width is adjusted to correspond to the object to be irradiated.

To understand the acceleration of the electrons in the accelerator the best way to compare this with a normal Cathode ray tube used in the old TV. Fig 1.

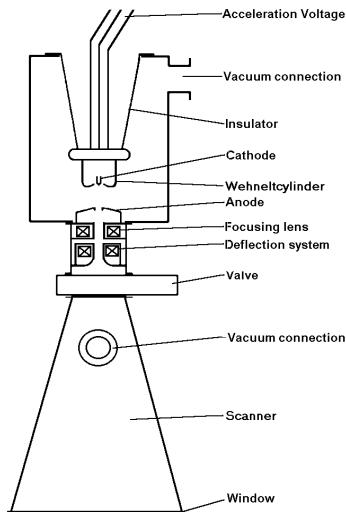


**Fig. 1 Cathode ray tube**

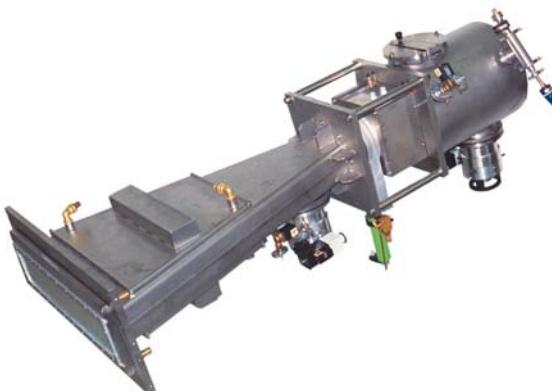
The production of free electrons in vacuum is properly familiar to us all from the cathode ray tube and the television tube. A classic triode system is used for generating and forming a beam. A tungsten cathode heated in high vacuum by an electrical current makes free electrons available on its surface and these are accelerated to the anode. In a TV set the electrons (negatively charged particles) are accelerated by a high negative voltage towards the anode and then deflected to the screen, or to the electron-beam exit window in the electron-beam accelerator. In the accelerator these electrons then emerge from the vacuum through a thin piece of titanium foil into the air or an inert gas where they can act upon the material.

### 3.1 Scanner system

In a scanner accelerators (fig.2) a tungsten heating cathode, Wehnelt cylinder and an anode -with focussing lens and electron-beam deflection system- together form one unit. Absolutely linear current signals control the beam deflection in two perpendicular directions. Scanning frequencies are over 800 Hz. The electron-beam exit window is designed to have a large surface area. A 7 to 20 microns thick titanium foil is supported on the vacuum side by means of a special construction.



**Fig. 2 Electron Crosslinking electron  
Electron accelerator Scanner type**



**Fig3. Picture of Electron Accelerator 250 kV  
accelerating voltage and 1,25 m working width.**

### Operating characteristics EC Scanner

- Acceleration voltage	75 - 300 kV
- Electron current	0 - 200 mA
- Working width	- 2000 mm- Throughput 9000 kGy m/min
- Distribution of dosage over working width	< ± 4 %
- No gas cooling of the electron exit window necessary.	
- The accelerator can be installed in any position whatsoever.	

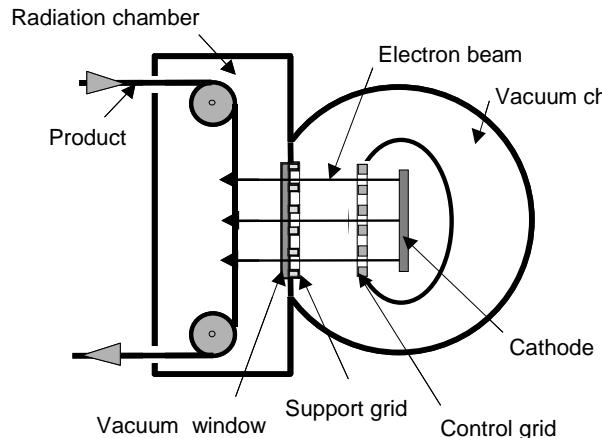
This type of accelerator is running at 24-hours operation in many different types of applications. It is especially distinguished by low set-up times following initial installation and service. Its uncomplicated construction combined with a control system for automatic process control enables the operator to quick and easy replacement of cathode and exit window without assistance from the supplier. Replacing wearing parts requires less than one hour in total.

Cooling is effected by means of water and convection through this supportive copper plate. No additional window cooling from the outside is necessary by blowing either air or inert gas. This considerably simplifies window cooling and the inerting of the process.

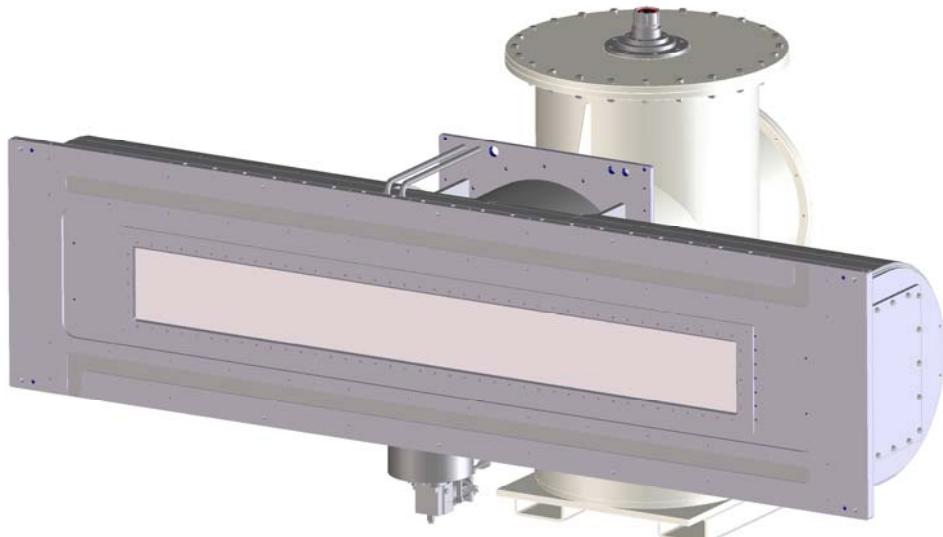
Scanner accelerators have the highest accuracy in dosage and distribution but are less powerful in emitting electron current. Their exactness makes these types ideal for product development and experimental use as well for production.

### 3.2 Linear or multi-cathode system

Linear or multi-cathode electron accelerators (fig. 4) utilize cathode systems with several cathodes across the working area. A control grid accelerates the electrons and guides them out of the electron exit window of titanium foil. These accelerators can easily be manufactured up to larger working widths (2-3 m). The linear accelerators provide a large electron current but are less accurate in the dosage and distribution, especially at low doses.



**Fig 4. Electron Crosslinking electron beam accelerator Linear type**



**Fig 5. Electron Crosslinking EC-beam working width 2,3 m.**

#### **Operating characteristics EC-beam**

- Acceleration voltage	75 - 250 kV
- Electron current	0 - 2000 mA
- Working width	400 - 3000 mm
- Throughput	14000 kGy m/min
- Distribution of dosage over working width	< ± 10 %
- No gas cooling of the electron exit window necessary.	



**Fig 6. Electron Crosslinking EC-print working width 600 mm**

#### **Operating characteristics EC-print**

- Acceleration voltage	70 - 110 kV
- Electron current	0 - 200 mA
- Working width	100 - 600 mm
- Throughput	6000 kGy m/min
- Distribution of dosage over working width	< ± 7 %
- No gas cooling of the electron exit window necessary.	
- The accelerator can be installed in any position whatsoever.	



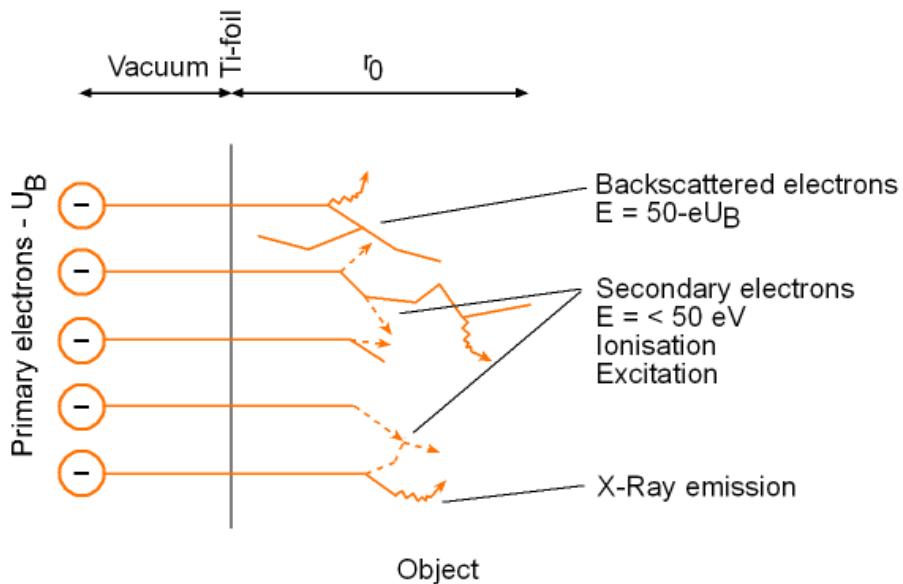
**Fig 7. Electron Crosslinking EC-tube working diameter 20 mm**

#### **Operating characteristics EC-tube**

- Acceleration voltage	70 - 140 kV
- Electron current	0 - 2 mA
- Tube diameter	20 mm
- Max diameter	ca 80 mm
- No gas cooling of the electron exit window necessary.	
- The accelerator can be installed in any position whatsoever.	

## 4. ELECTRON EFFECTS

Electrons are generated and accelerated in vacuum. They then proceed through the titanium foil from vacuum to normal atmosphere, and penetrate into the material with a range up to  $r_0$ . Electrons accelerated with the same voltage have a behaviour independent of the type of accelerator and can thus be used the same way. The main difference between the systems is the water cooled window construction supporting the exit window. In most cases the development can be made in laboratory scale before running in production scale. The calibration of the system is important and has to be done with a dosimetry system. [31]



**Fig. 8 Electron interactions with matter (schematically)**

After a distance of  $r_0$  all electrons are retracted due to interaction with the material.

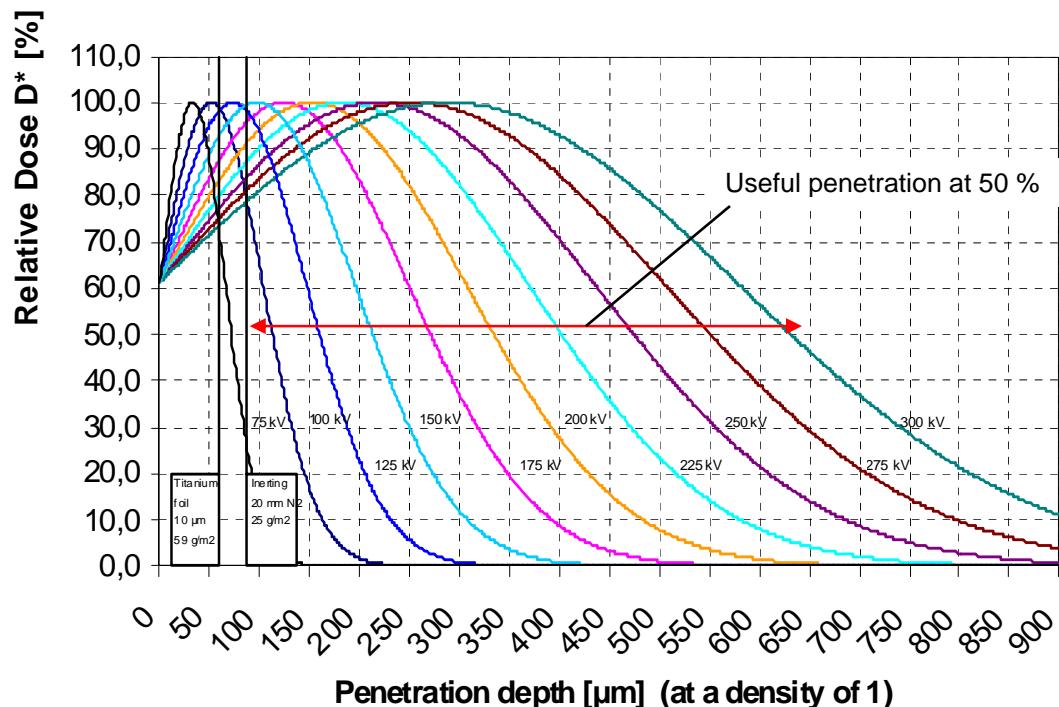
- Here Primary electrons / Backscattered electrons are generated. Their energy exceeds 50 eV and has a maximum corresponding to the accelerating voltage. The fast primary and backscattered electrons do not lead to chemical reactions. Their activation cross section is too low – they cannot be caught by molecules and thus do not lead to radical formation, ionization or excitation.
- Important to us are the Secondary electrons at energy levels between 3 and 50 eV. They are slow enough, i.e. their activation cross section is large enough to ionize molecules and to form radicals. Very slow electrons less than 3 eV only induce Excitation. Ultimately we only need the fast electrons to generate secondary electrons at the location outside the vacuum and/or deep in material.
- A negative by-product of retarding accelerated electrons is the X-ray emission. Its energy cannot exceed the primary electron energy. This means that the electron-beam accelerator and the irradiation zone have to be shielded to prevent X-ray emission.

An electron behaves similarly to a bullet: higher accelerating voltage means deeper penetration (higher  $r_0$ ) in the material. Penetration is depending only on the density of the material and the electrons can penetrate through metals.

#### 4.1 Depth of penetration

Penetrating power of the electron beam is related to the accelerating voltage and the density of the processed material. Higher voltage causes deeper penetration, and denser material reduces the depth of penetration. The Depth Dose Curves (Fig 6) are convenient aids for estimating the penetration depth. These curves show the penetration for different accelerating voltage to the depth of penetration in a material with mass density equal to that of water, i.e.  $\rho = 1 \text{ g/cm}^3$ .

Penetration into materials of different density can be estimated by multiplying the penetration depth, found from the normalized curves, by the ratio of the density of water to the density of the material. For example, a 200 kV beam will have a 50 % dose point at 0,246 mm in water and 0,123 mm in a material twice as dense ( $\rho = 2 \text{ g/cm}^3$ ).



**Fig. 9 Range of penetration with different accelerating voltage 13 μm titanium foil and 20 mm of Nitrogen. [22]**

At accelerating voltages of 150, 180 and 250 kV curing depth of 86, 138 and 277 g/m<sup>2</sup> respective are achieved at 80 % ionization.

The titanium foil and inerting space have influence on the depth dose distribution within the processed material in the low voltage region

#### 4.2 Absorbed Dose

Absorbed dose is defined as the amount of energy deposited into a specified mass of material. The unit of absorbed dose is gray (Gy), defined as the number of joules (J) of energy deposited into 1 kilogram (kg) of material. An older, but frequently used unit, is megarad (Mrad).

1 Gy = 1 J/kg	- Heating of water 1 degree	4,2 J/g
1 kGy = 1 kJ/kg	- Evaporation of water, at atm.	2250 J/g
1 Mrad = 10 kGy = 10 J/g = 2,4 cal/g	- EB-curing of lacquer approx.	40 J/g

At a fixed electron accelerating voltage, the dose  $D$  [kGy] is proportional to electron current  $I$  [mA] and inverse to web speed  $v$  [m/min] as follows:

$$D = k \times \frac{I}{v}$$

the  $k$  factor is depends on the equipment and the accelerating voltage.

The formula above shows:

- dose and electron current are directly proportional
- if the ratio of electron current and speed are kept constant the dose is constant including start up and shut down of the plant
- the accelerator uses only the quantity of power from the main supply needed for the used web speed
- quality improvements (no over or under curing)

## 5. APPLICATIONS

In all industrial applications the Electron Beam Accelerator itself is the same but the handling system differs for:

- Laboratory equipment
- Solid form materials, as sheet, board, panels, etc.
- Flexible material, roll to roll

### 5.1 Laboratory equipment

Laboratory scale serves as a basis to develop an in-depth fundamental physical and chemical understanding of the process, to investigate a wide variety of materials and methods for producing crosslink in materials, and to develop more effective, optimized treatments.

Pilot plants are small processing systems that are operated to generate more detailed information required for scale up to production plant. A detailed analysis leads to optimization of the process parameters.

Selection of material, paint and process design etc. should be based on the laboratory data from large-scale experiments in a laboratory Electron beam accelerator.

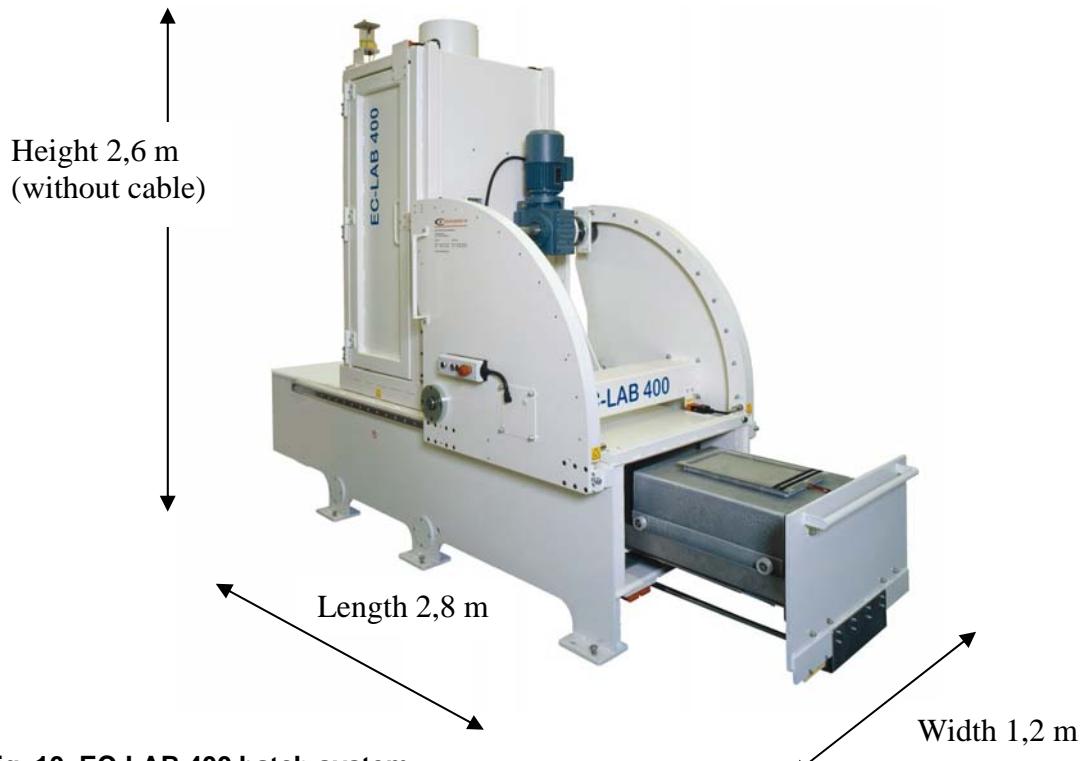
The EC-LAB 400 is a compact multi-purpose laboratory electron beam with a variety of possibilities and applications. These include web transport with drum and batch applications and there is option for continuous roller transport for adaptation in other processes and system for continuous irradiation of cables, fibres and composites that will open many new possibilities. The highly modular design it can easily be customized to meet unique needs and ambitions. The EC-

LAB equipment is suitable laboratory use or pilot scale production, to develop new processes or to insure quality in production. [30]

Process parameters and data from the EC-LAB 400 can be directLY translated to a production unit.

### Typical data for EC-LAB 400

Accelerating voltage:	80 – 300 keV	Cassette speed:	5 – 30 m/min
Electron current:	0 – 30 mA	Max size (LxWxH):	600 x 400 x 250 mm
Working width:	max 400 mm	Web speed:	0 – 150 m/min
Throughput:	4500 kGy m/min	Max web width:	450 mm
Exit window:	Titanium		
Thickness:	7 – 20 µm		



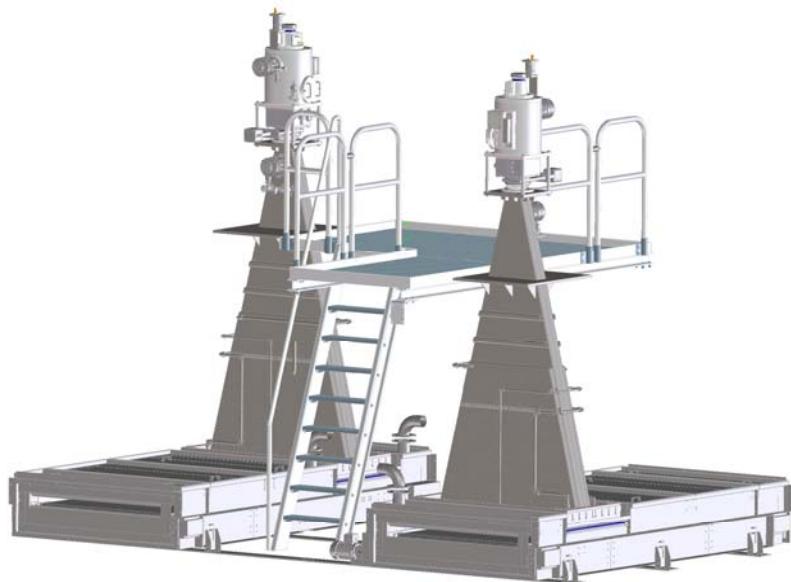
**Fig. 10. EC-LAB 400 batch system.**

## 5.2 Solid materials

In the surface converting of solid materials the EB-technology is successfully used in the following operating fields:

- Curing of top lacquer on doors [1], [2]
- All-around curing of coated profiles [3], [4]
- Curing of the coating on raw boards in the wood industry [5], [6]
- Curing of the coating on architectural claddings for outside applications [7], [8]
- Curing of the coating on wood-cement boards for outside and inside application [9]
- Curing of impregnation and top lacquer on laminated boards
- Curing of coated edges and panels in the wood and laminate industry [10]

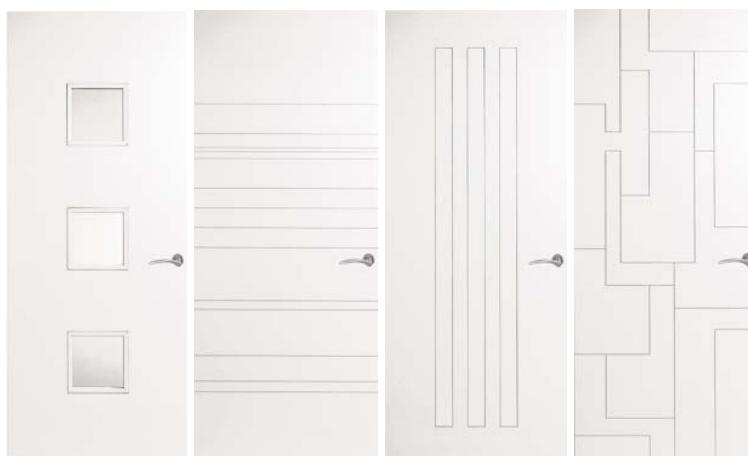
Curing of coatings on MDF boards (Medium-Density-Fibre-board) [11], [12], [13]  
 Curing of coatings on three-dimensional parts e.g. rims and pumps housings.  
 Surface sterilization and disinfection



**Fig. 11 Accelerator for door line**

#### **Operating characteristics EC-scanner**

- Acceleration voltage	80 - 250 kV
- Electron current	0 - 200 mA
- Working width	100 - 1350 mm
- Throughput	9000 kGy m/min
- Transport speed	0 - 50 m/min
- Production size (wxh)	1230 x 2600 mm
- Distribution of dosage over working width	< ± 4 %



**Fig. 12 Typical doors Svedex®**

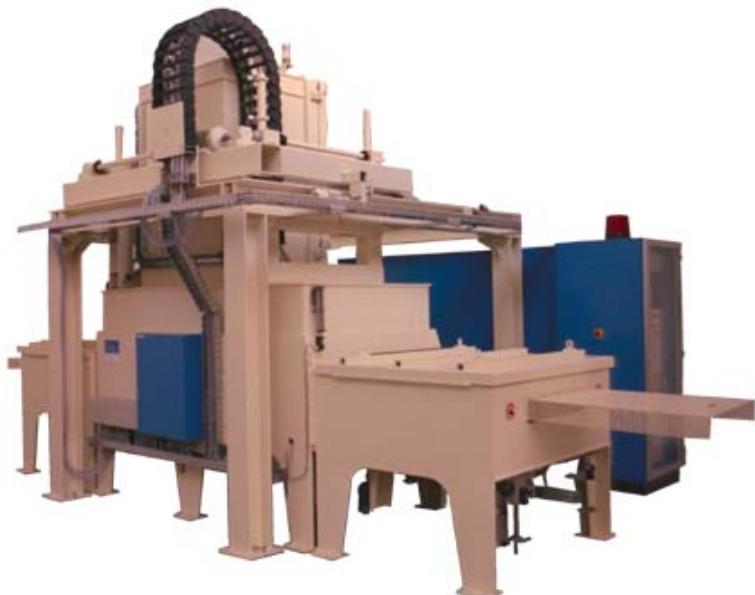


Fig. 13 Picture flat line

#### Operating characteristics EC-scanner

- Acceleration voltage	80 - 300 kV
- Electron current	0 - 100 mA
- Working width	100 - 600 mm
- Throughput	9000 kGy m/min
- Transport speed	0 - 35 m/min
- Production size (wxh)	600 x 600 mm
- Distribution of dosage over working width	< ± 4 %

Sterilisation of PET bottles is done by the EC-tube on the inside of the bottle to achieve Sal 10-6 degree and is a safe and fast way compared to method with steam and chemistry.

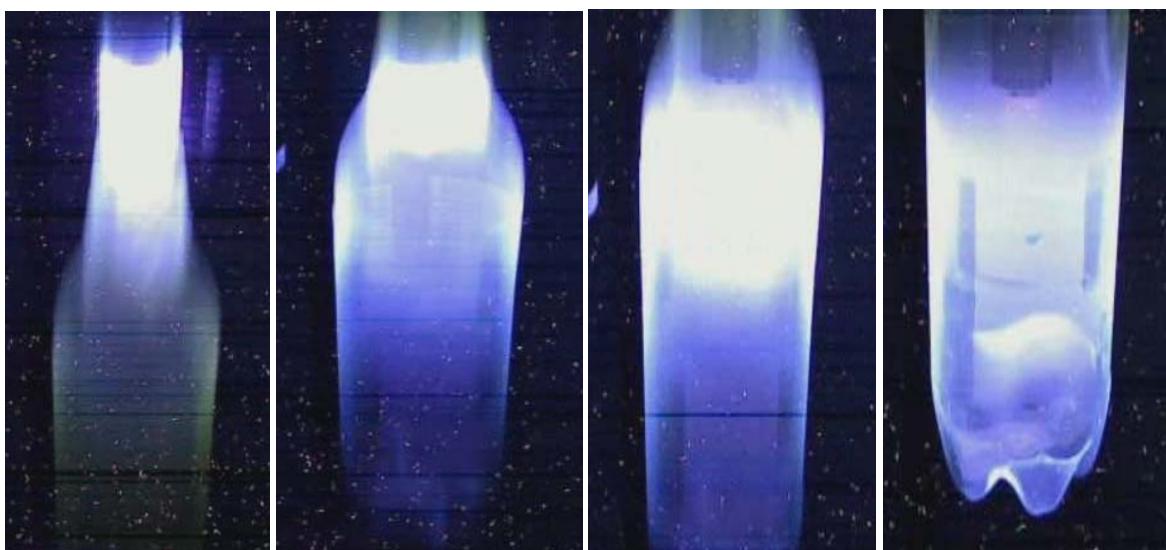


Fig. 14 Irradiation of Pet-bottles (Krones)

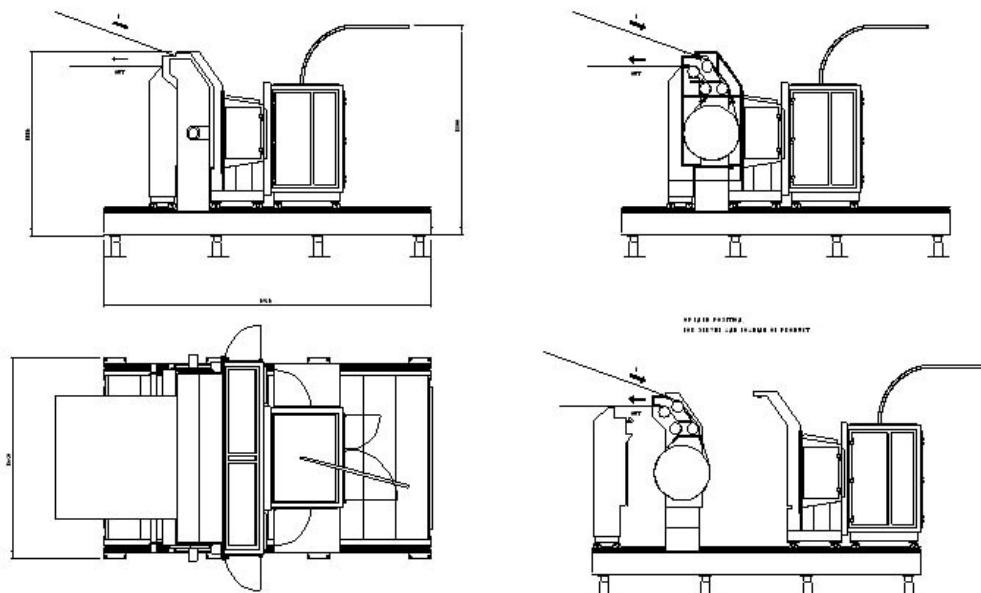
### Operating characteristics EC-tube

- Acceleration voltage	70 - 120 kV
- Electron current	0 - 2 mA
- Bottle type	PET 1,5 L
- Throughput	1 bottle / sec
- Sterility Assurance Level (SAL)	$10^{-6}$

### 5.3 Flexible materials

In the surface converting of flexible materials the EB-technology is successfully used in the following operating fields:

- Vulcanisation or Crosslinking of pressure-sensitive adhesives [14]
- Curing of high-gloss coating of special paper (e.g. photographic paper) [15], [16], [17]
- Curing of release coatings
- Curing of web offset printing inks, finishing varnishes [18], [21]
- Crosslinking of films and foils
- Production of antistatic finish
- Crosslinking of flock adhesives
- Curing of intaglio prints [18], [19], [20]
- Post-Crosslinking of binding agents of magnetic materials
- Metallizing of paper, e.g. curing of basic lacquer and adhesives for selective or plane transfer metallizing as well as curing of overprints
- Curing of metal coating from roll to roll (coil coating) [24]
- Stabilisation of rubber raw materials by partial vulcanisation
- Crosslinking of laminating adhesives
- Crosslinking of thin insulation of wire and cables
- Colouring of textiles
- Surface Sterilization



**Fig 15. Typical layout for flexible products**

### 5.3.1 EC-beam printing system

EC-print 110 is a compact Electron beam accelerator Linear type suitable for all Flexo-, Screen- and Rolloffset- printing applications up to 600m/min or more.

The costs for the HV transformer and screening can be reduced through lower accelerating voltage. The advantage of reducing the accelerating voltage is well known. This has however not been implemented as there have not been any thin foils available in corresponding sizes for the printing industry. The window foils of titanium used until now are manufactured by through rolling mill. Because of the high mechanical stress when making thin foil "pin holes" can be obtained. New techniques make it possible to manufacture thin foils without pinholes.



**Fig 16. Picture EC-print for Web width 600mm**

#### Typical data for EC-print 110-600

Accelerating voltage:	70 – 110 keV
Working width:	max 600 mm
Throughput:	6000 kGy m/min
Web speed:	0 – 600 m/min

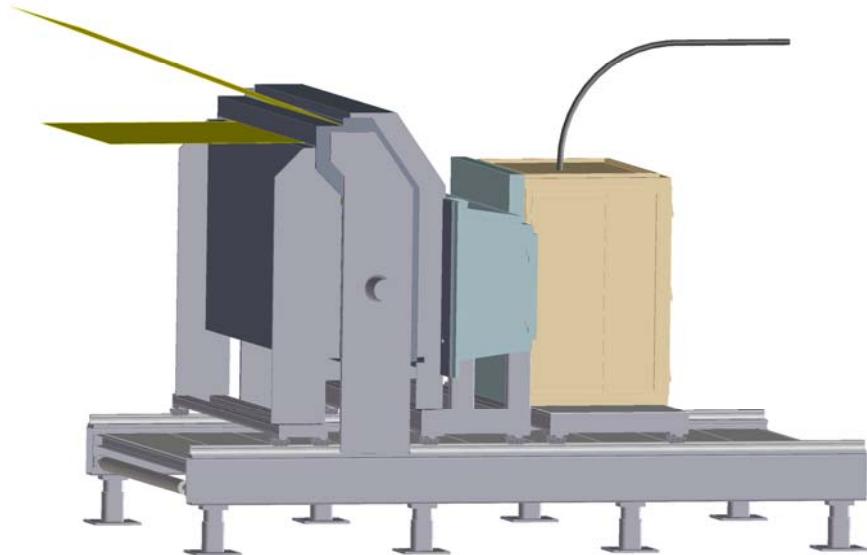
### 5.3.2 EC-beam 80-250kV

Electron beam suitable for curing and surface converting of a variety of substrates, e.g.:

- Wood materials such as floor coverings, doors, wall plates, all-around curing of lacquers on mouldings
- Façade plates for outside application, direct coatings of paper and foils
- Paper and synthetic foil coatings (furniture foils, lacquered foils for laminated boards in application for high requests like floor coverings or table surfaces)
- Vulcanizing of pressure sensitive adhesives

The PLC system of the equipment control and supervise the high voltage (penetration depth of electrons) and electron beam (dose / throughput of material).

The unit can be equipped with inert gas recovery and recirculation.



**Fig. 17. EC-beam 250kV Product width 2300 mm**

#### **Typical data for EC-beam 250kV**

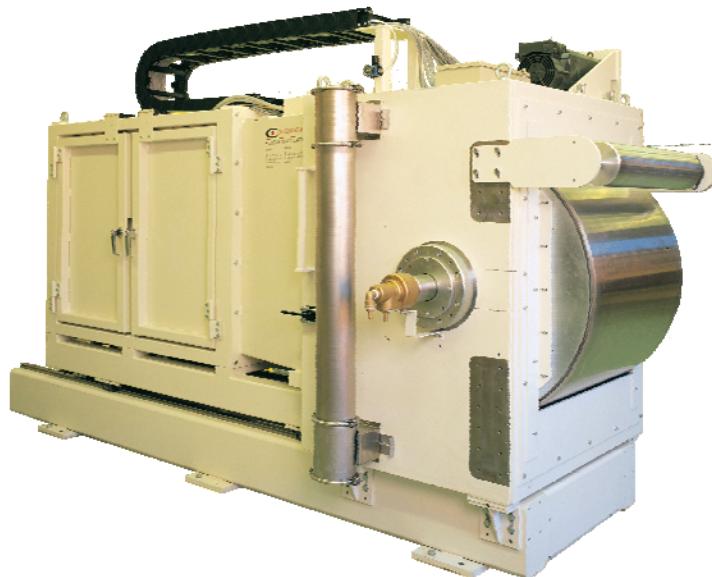
Production unit made for 24/7 operations at 250kV

Accelerating voltage: 80 – 250 keV

Working width: max 2300 mm

Throughput: 13000 kGy m/min at 150 keV

Web speed: 10 – further m/min



**Fig. 18. EC-scan unit for from roll to roll. (120 kV, 220 mA, 0,6 m)**

#### **Typical data for EC-scan 120kV**

Production unit made for 24/7 operations at 250kV

Accelerating voltage: 80 – 120 keV

Beam current 0 - 200 mA

Working width: max 600 mm

Throughput: 9000 kGy m/min at 150 keV

Web speed: 10 – further m/min

#### **5.4 EB –Package sterilisation**

The documentation of the radiation sterilization process rests on the ability to measure dose in all steps of the validation and routine control.

##### **5.4.1 Aseptic packaging.**

Consumer products such as aseptic packaging for food or cosmetics, which have to be microbe free, can be sterilized by radiation.

Sterilizing the inside of the package packaging production moves a considerable part of the aseptic process from dairies and other beverage companies back to packaging production. The sterilization is performed with electron beam inline treatment, which is a safe method with a low environmental impact. This process has no effect on material properties like strength or colour, nor does it generate any detectable odours. The package is sterilized throughout, and the irradiation process follows the ISO standard for medical products, thus ensuring defined package sterility levels.



**Fig. 19 EC-scan 120 kV**



**Fig 20. Ecolean® Air Aseptic**

#### Typical data for EC-scan 120kV

Production unit made for 24/7 operations at 250kV

Accelerating voltage: 80 – 250keV

Beam current 2 x 120 mA

Working width: max 400 mm

Throughput: 9000 kGy m/min at 150 keV

Web speed: 10 – 300 m/min

#### 5.4.2 Medical Device.

EB 300-120 MD

Electron accelerator manufactured according to GAMP [29].

Producers of medical devices have a responsibility to ensure that their products are free from viable microorganisms. Sterile medical devices meet a Sterility Assurance Level (SAL) of  $10^{-6}$  or less, i.e. the probability of a single viable microorganism being present is less than  $10^{-6}$ .

A minimum irradiation dose of 25 kGy is considered sufficient to validate the sterilization of a medical product [27]. An irradiation dose of 15 kGy is acceptable when bio burden is lower than 1,5 cfu [27].

Accelerated electrons in voltage ranges of 150 - 250 keV with penetration depth see Fig 8 (in material of density) 1 of 70 - 300  $\mu\text{m}$  are particularly suitable for

- Surface sterilization
- Germ reduction in the depth of the packaging material.



A key aspect for Medical device equipment is well written procedures. Procedures should be clear, concise and easy for employees to follow. Well-written procedures should not leave any room for misinterpretation. They should be written in such a manner that anyone who is properly trained and knowledgeable in the field could follow them as they are written should be clear, concise and easy for employees to follow. Well-written procedures should not leave any room for misinterpretation. They should be written in such a manner that anyone who is properly trained and knowledgeable in the field could follow them as they are written.

**Fig. 21 EB 300-120 MD**

## 6. SUMMARY

Advantages of Electron Beam curing:

- Environmentally friendly due to a 100 %-solid system. EB generates no emissions.
- No or low substrate heating.
- Low energy consumption.
- Substantial production increase compared to conventional heat-treatment methods and UV-technology, also with pigmented layers.
- Immediate further treatment of converted products without post curing.
- Low space requirement. Integration into existing production processes without any problems.
- Exact repeatability of production conditions is obtained due to high dose accuracy. There is also no wastage when starting up and shutting down the plant.

**EB curing is a very fast, energy efficient and environmentally friendly drying method that provides particularly hard and chemical resistant surfaces with controlled curing throughout the depth**

**Laboratory scale serves as basis to developing materials and methods for producing Crosslinking in materials**

**Pilot plants leads to optimization of the process parameters and ensure a successful transition to production.**

**Still in order to carry this technology on to success, good cooperation between customer, chemistry and plant manufacturers is necessary.**

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