

The Growing use of E-Beam & X-Ray for Sterilization – New opportunities & skills

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Intro & context

What is Electron beam accelerator ?



- Electron beams accelerators are particle accelerators.
- In this case, the particles being accelerated are electrons and the beam generated is the equivalent of beta radiation.
- The voltage is the force that accelerates the electrons.
- Electron energies typically vary from the keV to MeV range, depending on the depth of penetration required.
- The irradiation dose is usually measured in grays but also in Mrads (1 Gy is equivalent to 100 rad).





Ok but, how does it work? Some examples





Electron are generated by the e-gun, then accelerated by the electric field in the cavity:

$$\Delta E_c = F. x = q. E. x = q. \frac{V}{x}. x = q. V$$

After the first acceleration pass, the electron are curved by a magnetic field:

$$F = q.(E+v.B) = \frac{m.v2}{r} \Longrightarrow B.r = \frac{m}{q}.v$$

Important: electron are relativistic after first pass: v = constant !

E (e⁻)	50keV	1MeV	10MeV
β	0.41	0.94	0.99
γ	1.098	2.956	20.56







Typical RF consumption:

- 80kW for 1MeV at 107MHz 105kW for 1.1MeV at 107MHz
- 840kW for 3.3MeV at 107MHz
- 120kW for 1MeV at 352MHz

The Rhodotron: Basic acceleration and re-circulation





RF Cavity E-Gun Magnets Final Power Amplifier







~30 % less consumption

Typical RF consumption:

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RF Pulsing Principle & Advantages







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Data from F. Stichelbaut - MCNPX 2.7.0

What about lower energy machines ?

At lower energy: The Dynamitron







e-

Electrons bombarded with selected high energy on chosen material

Design key idea: to separate functions in order to better master them (master or avoid couplings, ...)

Irradiated material

































Dynamitron: a few pictures...









A few words about linacs ?

Linacs in a nutshell

Varian 600c biperiodic $\pi/2$ -mode SW structure:



Frequency Range	Microwave / Radar Bands	
216 — 450 MHz	P-Band	
1 — 2 GHz	L-Band	
2 — 4 GHz	S-Band	
4 — 8 GHz	C-Band	
8 — 12 GHz	X-Band	
12 — 18 GHz	K _u -Band	
18 — 26.5 GHz	K-Band	
26.5 — 40 GHz	K _a -Band	
30 — 50 GHz	Q-Band	
40 — 60 GHz	U-Band	
50 — 75 GHz	V-Band	
60 — 90 GHz	E-Band	
75 — 110 GHz	W-Band	
90 — 140 GHz	F-Band	
110 — 170 GHz	z D-Band	
110 — 300 GHz	mm-Band	



- Linear & compact structures
- Very common in medical and research industries
- Higher frequency = pulsed mode only at low duty cycle
- Variable energy possible
- Currently limited to 50-80 kW
- Lower electrical efficiency (losses & power RF sources)







Confidential

What are they used for and why?

What are electron accelerator markets?



Cancer Cell 000000



What are electron accelerator markets ?





"Global ebeam irradiation service market is expected to reach USD 1326.1 million by 2028, at a CAGR of 8% during 2022-2028" Electron Beam Irradiation Service Report 2023

Medical applications Food industry Cable & wiring industry Other industrial applications 27

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Why is sterilization special today ?













Why is sterilization special today ?







Why is sterilization special today ?





Volume of Sterilized Single Use Medical Devices

iba

The change of paradigm









Rhodotron® installed base 2024-2025



Yes, I am convinced ! How do we start ?

Where do we start?





Market Segment	Electron Energy	Typical Penetration
Surface Curing	80 - 300 keV	0.4 mm
Shrink film	300 - 800 keV	2 mm
Wire & Cable	0.4 - 3 MeV	10 mm
Sterilization	3 - 10 MeV	40 mm

- Select penetration = Energy (MeV)
- Define needed dose = d (Gray)
 - Choose current = I (mA)
 - Scanning width (cm)
 - Product speed (m.s-1)
- Dose rate ? Gray, kGray or MGray per second ?
- Energy stability & spectrum ?
- Lifetime ? 10 or 30 years ?
- Uptime ? 97% ? 8000 hours a year ?
- Cost to buy and maintain ? 1 or 20 M\$?
- Interface with Conveyor system ? Footprint ?
- Safety ? Shielding ?
- Electrical efficiency ? 20 or 75% ?
- Easy to find parts ? Obsolete when ?
- Time to buy and install ? 12 to 24 months ?
- Sustainability ? SF6 or not ?



Who can integrate something like this and make it work 8000 hours a year during 30 years ?







YOU PROVIDE THE URS:

- Packaging
- Batches
- Density
- Materials
- Can be flipped ?
- Target dose ?
- DUR ?
- Throughput ?
- Business case ?
- Business evolution ?



Side 1

- Side 2

DESIGN IS OPTIMIZED:

- Doses
- DUR
- Compatibility
- Throughput
- Ramp-up plan
- Conveyor first
- Accelerator
- Bunker/Facility
- Options
- IQ/OQ/PQ plan





Aerial & Monte Carlo to confirm in a real setup and with real products

- Product Testing
- Monte CARLO service
- Dose Mapping
- Packaging optimization
- Product design

Breaking: FLASH Feature is now available at aerial !





Total dose (side A + side B)

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What if I need more than 50 cm of penetration like gamma? Why is X-Ray booming now ?

Industrial Sterilization Processing Comparison





E-Beam or X-ray ?



X-Ray have more **Penetration**: \rightarrow Bigger **Packaging** \rightarrow Better **DURs** \rightarrow Better process **Quality**



 \rightarrow Easier dose transfer



Industrial Sterilization Processing Comparison







X-Ray fundamentals

Reminder from Webinar #4

What are X-Rays ?





Key messages Webinar #4

- X-rays are produced by Bremsstrahlung when incident electrons interact with the electromagnetic field of target nuclei.
- The incident energy of the electrons is limited to 5 or 7 MeV to avoid activation of the target and products.
- Conversion efficiency is typically 8 to 12%, the rest is heat.
- X-Ray exhibit a continuous energy spectrum between ~150 keV and the incident electron energy (T₀).
- X-Ray are neutral: they penetrate deeper than electrons and deposition follows a simple exponential decrease.
- Dose is deposited by secondary electrons: a photon is a photon



Key messages Webinar #4

- X-Ray convertors are optimized since the 80's to:
 - Maximize X-Ray conversion efficiency
 - Optimize X-Ray fields geometries
 - Reduce secondary electrons in the products
 - Optimize cooling design of target and horn
 - Maximize reliability and maintainability





The best DURs with the latest generation







Scan type	DUR	D _{min} (kGy/h/mA)	D _{max} (kGy/h/mA)
Uniform	1.57	0.52	0.81
Variable	1.44	0.63	0.90



Ok clear, back to process integration !



Shielding or Bunker Energy & process dependent

Beam scanning & dose control Linear, variable, continuous, pulsed

Accelerator: E-beam or X-Ray

Anciliaries

Dosimetry, control, electrical Ozone, maintenance Energy supply

Process Control System - PCS Recipes, control, monitoring, reporting Interface with ERP

The product conveyor: Box, tray, totes, pallets, wires, water, sludge

> **Building safety** According to regulations

> > Automatized warehouse Robots, AGV

BEYOND



"Lateral irradiation": Simple & cheaper No flipping Low to Medium throughput

"Top down irradiation": Medium cost Flipping of the boxes High throughput Very high with robots

THICKNESS + CONFIGURATION BOTH = DUO DENSITY CONSIDERATIONS TWO-SIDED GAMMA / HIGH **REQUIRED?** X-RAY Radiation PRODUCT Compatible VARIABILITY ? Material ? LOW E-BEAM DSTE - DMAX DESIRED **VOLUME**?

"X-Ray irradiation": Simplest conveyors No flipping High throughput without robots

YOND

An example: Lateral Irradiation of boxes





Product				
Av. Density (gr.cm ⁻³)		0.15		
Product Mix	Product Mix			
Performance				
DUR	< 1.8			
Volume (m³/yr)	up to 140,000			
System Properties				
Туре	Double side lateral by rotation			
Energy	10 MeV			
Scan	30-100 cm			
Power	20 to 80 kW			
Footprint	25 x 26 x 6 m			



State-of-the-Art Conveying Systems



X-Ray solution selection guide









1-Level / 2-Sided



- ► ~ 100 000 m³
- > 0.15 g/cm³
- ≻ 25 kGy
- > DUR : ~1.8 \rightarrow 1.3 with variable S



- ➢ Horn 2.2 or 3 m
- > Typical overscan ~20 cm



- > 1 level conveyor
 - > Vault height ~ 3 4 m



>

Treatment area : ~900 m²





Zoom on the 2 levels, 2 sides or "4 Sides"





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It's only box and pallets ?

Other examples of EB/XR integration







Other examples of EB/XR integration







Horizontal Detector Array



X-ray

Other examples of EB/XR integration







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What are the jobs in the Industry around accelerator integration ?

A wide panel of expertise and skills: meet the experts



What are the jobs needed to integrate a center ?







And on the Customer side ? ~30 jobs per site







How do we conclude ?



E-beam and X-Ray are exciting technologies

- Sterilization and X-Ray are booming but other applications are around the corner
- Most of the value is in good Integration
- New applications are to be discovered still
- The sector creates a lot of opportunities, and a new generation should emerge !

Let's work on it !

