report

Low, Medium Energy Electron Beams & X-rays: A Guide to the Technology Fundamentals and Applications

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Executive Summary

Irradiation technologies play a critical role in modern industrial processing, enabling applications ranging from sterilization and decontamination to advanced material modification. The International Irradiation Association (iia) supports the safe and effective use of these technologies, including gamma radiation, electron beams, and X-rays, across a wide range of sectors.

Among these technologies, low-energy electron beams (LEEB) have been widely adopted for applications requiring precise surface treatment. Operating in the kiloelectronvolt (keV) range—typically between 80 and 300 keV—LEEB systems provide controlled, shallow penetration depths that allow high-dose delivery to surfaces while minimizing impact on underlying materials. Their compact, self-shielded design further enables seamless integration into existing production environments, making them well-suited for inline processing applications such as surface modification and pathogen reduction.

Medium-energy electron beams (MEEB), generally defined within the range of 300 keV to 5 MeV, have historically seen more limited deployment but are gaining increased attention. Advances in system design now allow for self-shielded configurations under certain energy and power conditions, expanding their applicability for both inline and end-of-line processing. These systems offer greater penetration capability than LEEB while maintaining operational flexibility.

Low-energy X-ray technologies complement electron beam systems by providing enhanced penetration and versatility for both sterilization and imaging applications. Their growing adoption in industries such as medical device manufacturing, pharmaceutical processing, and food treatment is driven by their ability to support continuous processing and offer cost-effective alternatives to higher-energy irradiation systems.

This paper provides an overview of low- and medium-energy electron beam technologies, as well as low-energy X-ray systems, focusing on their fundamental operating principles, current industrial applications, and emerging opportunities as compared to high-energy beams. The continued development and deployment of these technologies are expected to play an increasingly important role in meeting evolving industry demands for efficiency, safety, and scalability.

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1. Introduction

1.1 Energy Ranges

Electron beam and X-ray technologies used in industrial irradiation are typically categorized by energy range, as this parameter fundamentally determines penetration depth, shielding requirements, system design, and application suitability.

Low Energy Electron Beams (LEEB)

Are defined by ASTM 51818 as electron beams with energies at or below 300 keV[1]. These systems, sometimes referred to as emitters or lamps, operate using direct current (DC) high-voltage generation. Standard vacuum technology can reliably sustain potential differences up to approximately 300 kV, enabling continuous electron generation from point or surface sources.

At these low energies, electron penetration depths are limited, resulting in steep dose gradients. This creates challenges for dosimetry, as electrons may be fully absorbed within the thickness of the dosimeter material. Additionally, stopping power increases significantly as energy decreases in this regime, where the relativistic gamma factor remains below approximately 1.5. Shielding requirements are relatively modest and can typically be integrated into the system using steel, lead, or layered combinations, enabling compact and self-shielded designs.

Medium Energy Electron Beams (MEEB)

Span the range from 300 keV to approximately 3–5 MeV. In this regime, electron stopping power changes rapidly, and the relativistic gamma factor increases from roughly 1.5 to 6. Unlike LEEB systems, these higher energies cannot be sustained using simple DC voltage systems. Instead, beam generation requires either alternating current (AC)-driven high-voltage systems or radio frequency (RF) cavity accelerators.

MEEB systems may operate in continuous wave (CW) or pulsed modes. While CW systems provide a steady beam with high-frequency structure (typically in the MHz range), higher power operation often necessitates pulsing to manage thermal loads within the accelerating structures. Pulse frequencies may range from tens of hertz to kilohertz, with duty cycles typically below 10%.

Although shielding requirements increase with energy, systems operating below approximately 5 MeV can often still be designed as self-shielded units, depending on beam power. While electrons are readily attenuated, their interaction with matter generates bremsstrahlung X-rays, which are more penetrating and therefore dictate shielding design. Typical shielding solutions involve steel and/or lead with thicknesses on the order of 30–100 cm, allowing installation without the need for dedicated radiation bunkers.

High Energy Electron Beams (HEEB)

Generally refer to systems operating above approximately 3–5 MeV.
At these energies, electrons are relativistic to highly relativistic, and stopping power becomes a slowly varying function of energy. As a rule of thumb, energy loss is approximately 2 MeV per $g \cdot cm^{-2}$. These systems are typically generated using RF cavity accelerators and may operate in either CW or pulsed modes.

Due to increased penetration and secondary radiation production, HEEB systems require substantial shielding, typically in the form of permanent, reinforced concrete bunkers. In contrast to lower-energy systems, dosimetry at these energies is well established, with a wide range of validated measurement techniques available.

The transition between MEEB and HEEB is not sharply defined. For the purposes of this paper, the following classifications are used:

- **LEEB:** 80–300 keV (per ASTM 518181)
- **MEEB:** 300 keV–5 MeV, where system design allows for self-shielding or modular shielding solutions
- **HEEB:** ≥5 MeV, where permanent shielding infrastructure is required

X-ray technologies are similarly categorized:

- **Low Energy X-ray (LEX):** 0.15–1 MeV
- **Medium Energy X-ray (MEX):** 1–5 MeV (generally considered impractical for most applications)
- **High Energy X-ray (HEX):** 5–7.5 MeV

1.2 Low Energy Electron Beam Technology (LEEB)

Low energy electron beams are typically generated using direct voltage accelerators, which are compact, relatively simple to operate, and cost-effective. Unlike gamma-based irradiation systems, electron beam accelerators can be switched off when not in use and do not involve radioactive materials, eliminating concerns related to radioactive waste.

These systems generally operate in continuous mode, delivering high dose rates—often on the order of 12,000 kGy·m/min—and are commonly designed to be self-shielded. This enables direct integration into production lines without the need for dedicated shielding facilities.

Due to their low energy, electrons penetrate only short distances into materials. Penetration depth is determined primarily by beam energy and material density, allowing precise control through adjustment of accelerating voltage. As a result, LEEB systems are particularly well suited for surface treatments of solid materials and thin liquid layers.

Electrons are generated in vacuum and must pass through a window to reach the target material. At low energies, both the window design and the intervening atmosphere significantly influence beam transmission and energy distribution. Electron scattering results in a diffused "cloud" beyond short distances from the window, requiring careful system design to maintain dose uniformity and process efficiency.

Surface (two-dimensional) emission systems are feasible at these energies. However, achieving uniform dose distribution requires precise control of emitter geometry and electric field configuration.

1.3 Medium Energy Electron Beam Technology (MEEB)

Medium energy electron beams are produced using technologies such as insulated core transformers (ICTs), Dynamitrons, and RF accelerators. These systems are more complex and capital-intensive than LEEB systems, often requiring additional subsystems including high-voltage power supplies, RF generators, and dedicated vacuum systems.

Unlike LEEB, MEEB systems generate focused beams with diameters typically ranging from 0.5 cm to several centimeters. To achieve uniform coverage, the beam is often magnetically scanned across the product, creating a two-dimensional irradiation field.

MEEB technology has been widely used in industrial applications for decades, particularly where greater penetration depth is required. It effectively bridges the gap between surface-limited LEEB processing and deep-penetration HEEB systems.

The wire and cable industry represents one of the most established applications of MEEB technology, where high-throughput crosslinking processes provide enhanced product performance, including improved thermal resistance, mechanical strength, and chemical durability.

More recently, MEEB systems have gained traction in emerging applications such as medical device sterilization, advanced materials processing, and energy technologies (e.g., batteries, fuel cells, and specialty membranes). These systems enable treatment of packaged or dense products while maintaining high throughput and allowing on-site processing, reducing reliance on off-site irradiation facilities.

Compared to higher-energy systems, modern MEEB installations benefit from reduced facility complexity, improved shielding efficiency, and lower overall infrastructure requirements. They offer a balanced combination of penetration capability, throughput, and energy efficiency, particularly when replacing conventional thermal or chemical processing methods.

1.4 Low Energy X-ray Technology (LEX)

X-rays are generated indirectly by directing accelerated electrons onto a high atomic number (high-Z) target material, such as tungsten or tantalum. This interaction produces bremsstrahlung radiation, converting a portion of the electron energy into X-rays.

At low energies, this conversion process is inherently inefficient, with theoretical efficiencies ranging from approximately 2.5% at 300 keV to about 12% at 3 MeV. In practice, actual efficiencies are often lower, with the majority of energy dissipated as heat within the target. Effective thermal management is therefore critical in system design.

The resulting X-ray spectrum is complex and depends on multiple factors, including electron beam characteristics, target composition and thickness, filtration materials, and system geometry. Unlike electrons, which have well-defined penetration ranges, X-rays exhibit exponential attenuation, with penetration determined by the higher-energy components of the spectrum.

Modern X-ray tube systems integrate the electron source, accelerating components, and target within a sealed vacuum enclosure. At sufficiently low energies (often below 300 keV), these systems can be designed as self-shielded units, enabling compact, cabinet-style installations.

In addition to imaging, LEX technologies are increasingly used in applications such as blood irradiation, sterile insect technique programs, and cannabis decontamination. The transition from radionuclide-based systems (e.g., cesium sources) to electrically generated X-ray systems has been successfully demonstrated in several of these applications, driven by safety, regulatory, and operational considerations[2].

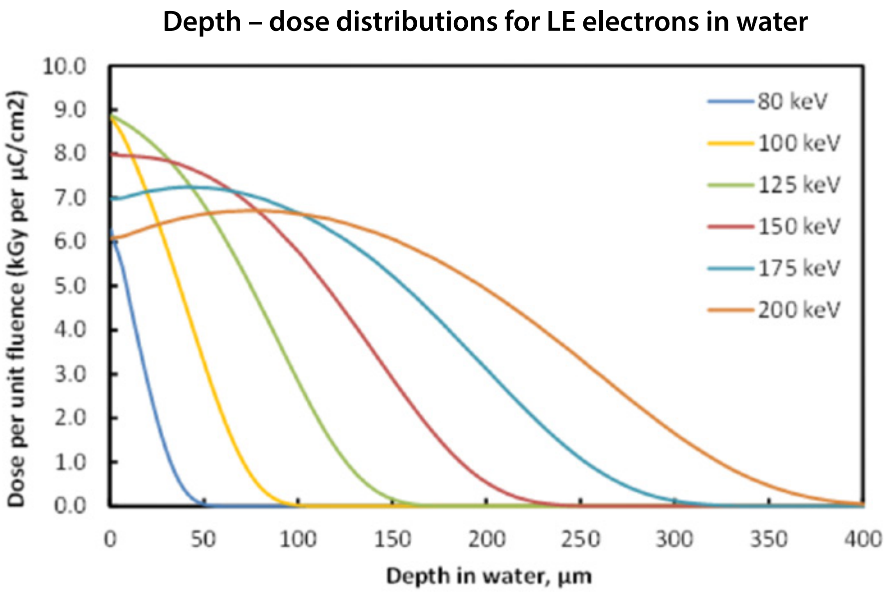
2. Dosimetry Considerations

Dosimetry for electron beam and X-ray irradiation systems is strongly influenced by particle energy, penetration depth, and dose distribution characteristics. These factors are particularly critical at low and medium energies, where steep dose gradients and limited penetration introduce unique measurement challenges.

2.1 Dosimetry for Low Energy Electron Beams (LEEB)

Low-energy electrons deposit their energy over very short distances, resulting in highly non-uniform depth-dose profiles. As illustrated in **Figure 1**, electrons rapidly lose energy and come to rest within micrometers to millimeters, depending on their initial energy. This steep gradient complicates accurate dose measurement, particularly near the surface.

Figure 1: Depth-dose distributions for electrons in water. EGSnrc Monte Carlo calculations, approximately 10 µm Ti exit window, 10 mm air gap.



Because of this limited penetration:

- Conventional pellet dosimeters are not suitable, as electrons may not fully traverse the detector volume.
- Instead, **thin-film dosimeters** are required to achieve meaningful measurements.

Commonly used systems include:

- Radiochromic films such as Risø B3 and Far West FWT-60
- Thin alanine film dosimeters (approximately 135 µm thickness)

These dosimeters enable high spatial resolution and are better matched to the shallow penetration characteristics of LEEB.

2.2 Surface Dose Determination

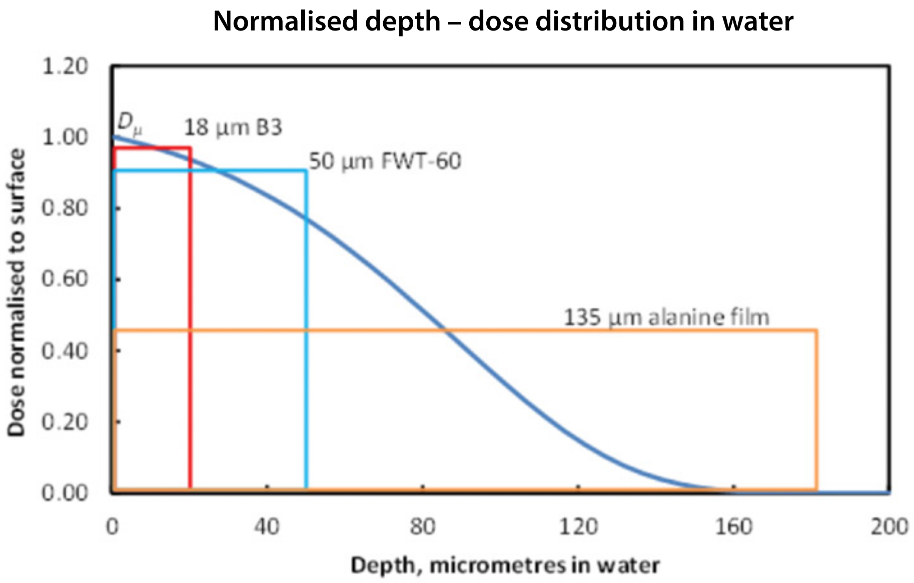
For many LEEB applications, the surface dose is the critical parameter. Determining this value requires reconstruction of the depth-dose distribution at or near the material interface.

A common approach involves:

- Using stacks of thin-film dosimeters (e.g., B3 films) to measure the depth-dose profile
- Applying **traceable alanine dosimetry** to establish calibration

As conceptually illustrated in **Figure 2**, the measured dose in a dosimeter represents an average over its thickness. This must be correlated to the surface dose (Dµ)[3], defined as the dose to water within a 1 µm surface layer.

Figure 2: Illustrating the relationship between the average dose measured in a dosimeter and the surface dose, Dµ. The height of each colored box corresponding to a given dosimeter illustrates the average dose recorded by that dosimeter.



Corrections are required to account for:

- Nonlinear dose-response behavior of alanine
- Irradiation temperature effects

Even with these corrections, current methodologies typically yield uncertainties exceeding 10% (k = 2), highlighting the inherent complexity of surface dosimetry at low energies.

2.3 Process Dosimetry and Qualification

In industrial settings, dosimetry requirements are often application-specific and are established during:

- **Operational Qualification (OQ)**
- **Performance Qualification (PQ)**

During these phases, the relationship between:

- Measured dosimeter response
- Actual surface or target dose

is determined for a given product, geometry, and facility configuration.

Once validated, **routine process monitoring** can rely on:

- Apparent dose measurements from film dosimeters
- Correlated surrogate measurement techniques

This approach enables consistent process control without requiring continuous direct measurement of surface dose. Further guidance is available in established standards and technical publications[1,4].

2.4 Dosimetry for Low Energy X-rays (LEX)

Dosimetry for low-energy X-rays presents different challenges due to their exponential attenuation behavior and energy-dependent detector response. Optical dosimeters, such as Gafchromic MD-V3 films are commonly used for dose ranges up to approximately 100 Gy.

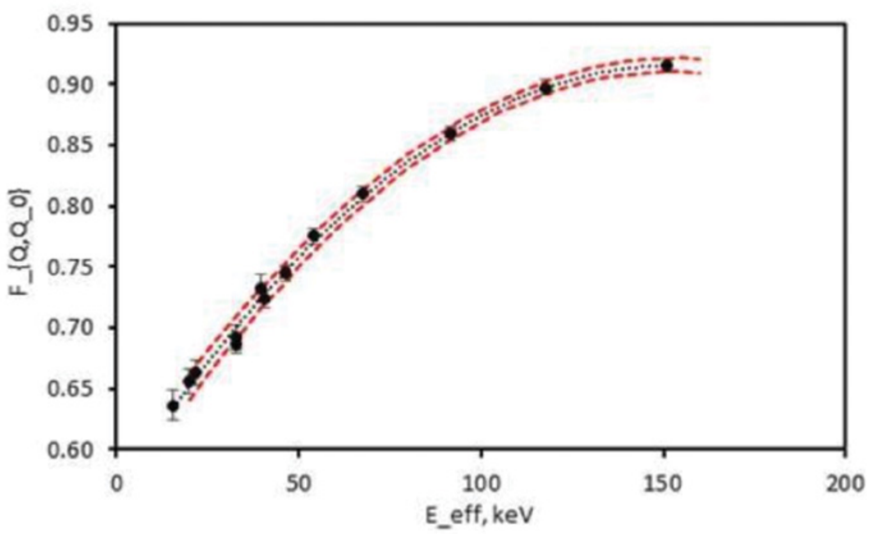
However, when traceable dosimetry is required, alanine dosimeters may still be employed. It is important to note that alanine response is strongly dependent on photon energy.

As shown in **Figure 3**, the relative response of alanine decreases significantly at lower photon energies. For example:

- At ~155 kV X-ray energies (typical of blood irradiators), alanine response may be approximately 16% lower than for cobalt-60 reference radiation.

This energy dependence must be carefully accounted for in calibration and dose interpretation[5].

Figure 3: Relative response of alanine as a function of effective energy (Data from Anton, 2015[6]).

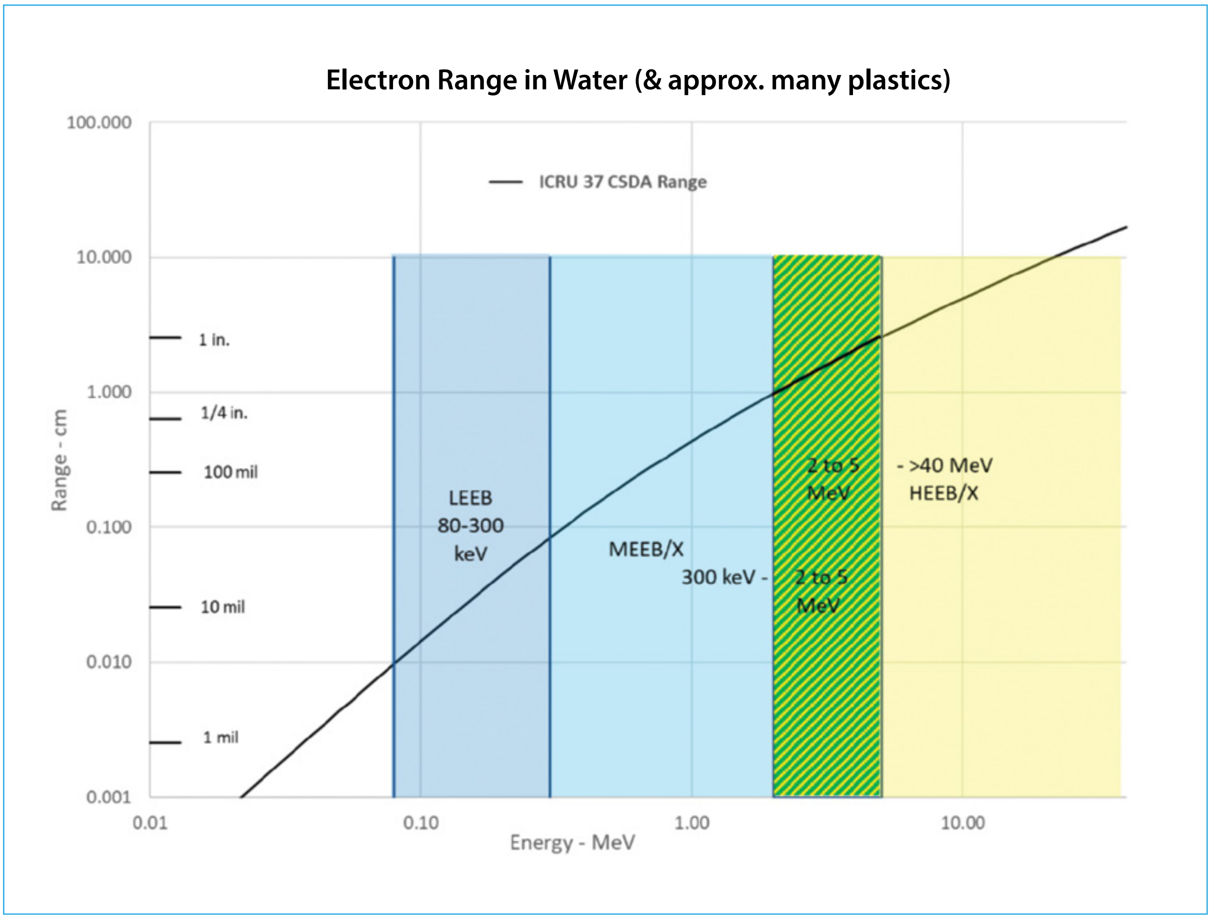


2.5 Penetration and Its Impact on Dosimetry

Penetration depth is a fundamental parameter influencing dosimetry strategy across all irradiation technologies, as shown in **Figure 4**. In essence:

- **Figure 4** illustrates electron range in water as a function of energy, showing the rapid increase in penetration from LEEB to MEEB and HEEB regimes.
- Many industrial materials, particularly polymers, have similar densities (~1 g/cm^3), making these curves broadly applicable.

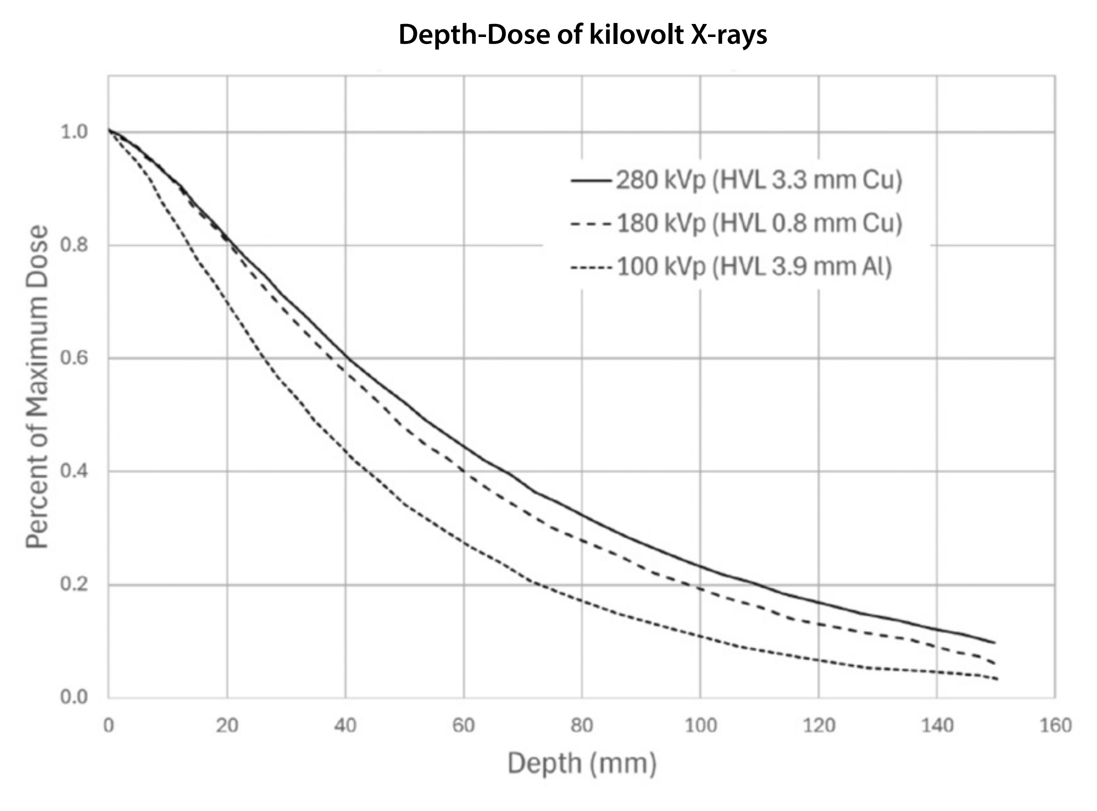
Figure 4: The range of electrons in water as a function of energy. Many plastics have a similar density, ~1g/cc, of low atomic weight elements, and so have similar ranges. Also shown on the left-hand scale are common distances in imperial units[7].



For X-ray systems:

- **Figure 5** demonstrates penetration depth behavior for low-energy X-rays
- Filtration (e.g., aluminum or copper) is often used to remove low-energy photons and achieve more uniform dose distribution

Figure 5: Penetration depth of low energy X-rays. Filters such as aluminum or copper are used to remove lowest energy photons for more uniform penetration.



These figures collectively highlight how increasing energy:

- Reduces dose gradients
- Simplifies dosimetry
- Expands usable application thickness

2.6 Comparative Perspective Across Energy Ranges

The practical implications of energy-dependent penetration and shielding are summarized in **Table 1**, which compares LEEB, MEEB, and HEEB/X-ray systems.

This comparison underscores several key points:

- Penetration depth increases significantly with energy, transitioning from surface-limited treatment (LEEB) to bulk irradiation (HEEB/HEX)
- Shielding requirements scale accordingly, moving from fully self-shielded systems to facilities requiring dedicated concrete bunkers
- MEEB occupies a critical intermediate space, offering meaningful penetration while still enabling flexible and potentially self-shielded system designs

The table provides a concise framework for understanding how dosimetry approaches, facility requirements, and application capabilities evolve across energy regimes.

Table 1: Comparison of properties of LEEB to MEEB to HEEB/X.

Parameter	LEEB	MEEB	HEEB/HEX
Penetration*	0.1 - 3 mm	3 mm – ~3.5 cm	~3.5 – 5 cm (10 MeV)
Shielding types	Self shielded	Self shielded or concrete	concrete

*in water, 1 g/cc.

2.7 General aspects of dosimetry

As noted above, dosimetry complexity is strongly dependent on irradiation energy, with the most significant challenges occurring at lower energies. In low energy electron beam (LEEB) systems, dosimetry is inherently difficult due to extremely shallow penetration and steep dose gradients. Accurate measurement requires specialized thin-film dosimeters and careful interpretation of surface dose, as conventional dosimetry methods are generally not suitable. The need to correlate measured dose to a defined surface layer further adds uncertainty and complexity.

As energy increases into the medium energy electron beam (MEEB) range, dosimetry becomes more manageable. Greater penetration depth reduces dose gradients and allows for more flexibility in detector selection and placement. While careful calibration and process validation remain essential, the broader dose distribution enables more practical and reproducible measurement approaches compared to LEEB systems.

At high energies, including high energy electron beams (HEEB) and X-ray systems, dosimetry methodologies are well established and widely standardized. Increased penetration results in more uniform dose distributions, simplifying measurement and improving accuracy. A wide range of validated dosimetry systems can be applied, making these technologies more straightforward to monitor and control from a dosimetric perspective.

3. Applications

Low- and medium-energy electron beam and X-ray technologies are used across a wide range of industrial, medical, and scientific applications. These include polymer modification, surface treatment, sterilization, food safety, vaccine production, and advanced manufacturing processes. Their versatility stems from the ability to precisely control dose, penetration depth, and processing conditions, enabling both surface-specific and volumetric treatments.

Low Energy Electron Beam Applications

Low energy electron beam (LEEB) technologies are widely used in both industrial and medical applications due to their combination of shallow to moderate penetration, compact system design, and the ability to operate without radioactive sources. LEEB is well established in curing coatings, inks, and adhesives. Emerging applications include sterilization and contamination control where precise selection of the application of dose is required such as sensitive medical devices, pharma, and vaccine development and production.

Low Energy X-ray Applications

Low energy X-ray (LEX) systems are widely used across medical, industrial, and security applications due to their ability to provide deeper penetration than low-energy electrons while still enabling compact, self-shielded system designs. In healthcare, they are extensively used for diagnostic imaging in medical and dental radiography, while in industrial settings they support non-destructive testing, quality assurance, and in-line inspection of manufactured products. Security applications include baggage and cargo screening, as well as contaminant detection in food production systems. Increasingly, LEX technology is also being adopted for irradiation-based applications such as blood irradiation, sterile insect technique (SIT), and surface decontamination processes. The transition from radionuclide-based systems to electrically generated X-ray units has further expanded their use in research and controlled irradiation environments, driven by improved safety, regulatory simplicity, and operational flexibility offered by self-contained, cabinet-style systems.

Medium Energy Electron Beam Applications

Medium energy electron beam (MEEB) systems are widely used in industrial processing where greater penetration depth is required than is achievable with low energy systems, while still maintaining high throughput and operational flexibility. A primary application is the crosslinking and modification of polymer materials, including wire and cable insulation, heat-shrink products, multilayer films, rubber components, foams, and molded parts. In these applications, MEEB enables bulk modification of material properties, improving thermal stability, mechanical strength, and chemical resistance. Beyond polymer processing, MEEB is increasingly used in medical device sterilization, advanced materials development, and energy-related technologies such as battery separators, fuel cell membranes, and specialty composites. The ability to process packaged or higher-density products, combined with reduced infrastructure requirements compared to high-energy systems, makes MEEB a versatile and economically attractive solution for both established and emerging industrial applications.

Medium Energy X-ray Applications

Medium energy X-ray (MEX) systems, typically defined in the range of approximately 1–5 MeV, are generally less widely deployed than electron beam or low energy X-ray systems.
In this case, the increased penetration over a LEX system is not significant enough compared to the inefficiency and system complexity considerations. However, where implemented, they provide enhanced penetration capability compared to low energy X-rays, enabling treatment of denser or larger-volume products without the need for direct electron access. Potential applications include sterilization of bulk medical products, pharmaceutical processing, and specialized industrial irradiation tasks requiring deeper dose uniformity within packaged goods. Despite these advantages, medium energy X-ray systems remain relatively limited in industrial adoption, primarily due to lower conversion efficiency, higher shielding requirements, and the availability of more practical alternatives in both low energy X-ray and high energy electron beam systems.

3.1 Polymer Modification

Radiation-induced polymer modification represents the largest-volume application of electron beam technology. Exposure to electron beams can induce crosslinking, polymerization, grafting, or chain scission, depending on the material and processing conditions.

A well-established example is crosslinked polyethylene (PEX), widely used in wire and cable insulation. Electron beam irradiation enhances material properties such as:

- Thermal resistance
- Mechanical strength
- Chemical durability

These improvements enable polymers to perform reliably in demanding environments, including automotive, rail, aerospace, and infrastructure applications.

Beyond wire and cable, electron beam processing is used in:

- Heat-shrinkable materials
- Multilayer films and foams
- Pipes and tubing for water and gas systems
- Molded and composite components

This broad applicability underscores the importance of irradiation in producing high-performance polymer systems.

3.2 Surface Treatment of Metals and Additive Manufacturing

Electron beam treatment of metal surfaces enables localized modification of material properties. Due to the shallow penetration of electrons in metals, rapid heating and cooling can produce surface layers with enhanced properties, such as[8]:

- Corrosion resistance
- Wear resistance
- Hardness
- Antimicrobial characteristics

In addition, electron beams are widely used in metal additive manufacturing, where they selectively fuse metal powders layer by layer to produce complex geometries[9]. This approach has evolved from prototyping to full-scale production, particularly for high-value components in aerospace and medical industries.

3.3 Electron Beam Curing

Electron beam curing is a solvent-free process used to harden coatings, inks, and adhesives. By initiating polymerization without chemical initiators, it offers:

- Rapid curing speeds
- Reduced environmental impact
- Improved product performance

Applications include:

- Scratch-resistant coatings for flooring and wall coverings
- High-gloss printing inks on packaging and labels
- Durable coatings in automotive and industrial products

The ability to cure materials instantly and inline makes this technology highly attractive for high-throughput manufacturing environments.

3.4 Electron Beam Welding

Electron beam welding utilizes highly concentrated energy to join materials with exceptional precision. The process allows:

- Deep, narrow welds
- Minimal heat-affected zones
- High repeatability and control

It is particularly suited for applications requiring high integrity and precision, such as aerospace components, automotive systems, and specialized industrial assemblies.

3.5 Electron Beam Grafting

Electron beam grafting enables the modification of material surfaces by bonding functional molecules without the need for chemical initiators. This technique can impart new properties such as:

- Increased durability
- Chemical functionality
- Improved adhesion

Applications include:

- Functionalized membranes with extended service life
- Textile treatments for wash resistance, odor control, and flame retardancy
- Battery materials and adsorbents

In biomedical applications, low-energy electron beams can be used to create surfaces that promote cell adhesion or incorporate antimicrobial functionality, supporting advanced medical device development.

3.6 Electron Beam Sterilization

Electron beam sterilization is widely used to inactivate microorganisms on medical devices, packaging, pharmaceuticals, and consumer products. This process is standardized by ISO 11137 which outlines the validation pathways for IQ/OQ/PQ for gamma, electron beam and x-ray technologies[10].

High-energy electron beams are typically used for bulk sterilization of packaged goods. In contrast, low-energy electron beams are particularly effective for:

- Surface sterilization
- Thin materials
- Applications requiring controlled penetration depth

This is especially important for:

- Pharmaceutical packaging
- Smart packaging with embedded electronics
- Medical devices with sensitive internal components

Low-energy systems enable sterilization of surfaces without damaging underlying materials, supporting the growing demand for advanced and integrated product designs.

3.7 Vaccine Production and Liquid Treatment

Low-energy electron beam irradiation of liquids has emerged as a promising technology for vaccine production. By precisely controlling penetration depth and delivering high dose rates, thin liquid films can be effectively treated.

A key advantage is the ability to inactivate pathogens while preserving antigenic structures, in contrast to high-energy irradiation[11], resulting in effective vaccines without the need for chemical inactivation. his approach has been actively investigated over the past decade and shows strong potential for broader adoption.

Additional emerging applications include:

- Cell therapy processing
- Wastewater treatment to accelerate degradation of contaminants
- Induction of targeted mutations for biotechnology applications

3.8 Food Treatment

Irradiation is widely used to improve food safety and extend shelf life. Low-energy electron beams are particularly well suited for surface decontamination, where pathogens are typically concentrated.

Key benefits include:

- Reduction of harmful microorganisms
- Extension of shelf life
- Prevention of spoilage and food waste
- Elimination of pests in agricultural trade

Applications include seeds, grains, nuts, spices, and fresh produce. Because of limited penetration, the bulk properties of the food remain unchanged.

The safety of food irradiation has been confirmed by organizations such as the World Health Organization and is approved in many countries worldwide. Use cases continue to expand, including quarantine treatment of imported fruits (e.g., mangoes and pineapples) to eliminate invasive pests.

3.9 Sterile Insect Technique (SIT)

The Sterile Insect Technique (SIT) uses irradiation to control pest populations by sterilizing male insects. Electron beam and X-ray technologies are increasingly being adopted as alternatives to gamma-based systems.

Key advantages include:

- Precise dose control
- Very short exposure times (milliseconds)
- No radioactive sources
- On-demand operation (system can be turned on/off)

Typical doses range from 35 to 120 Gy, sufficient to damage reproductive DNA while maintaining insect viability and competitiveness.

Although low-energy X-ray production is relatively inefficient energetically, it remains a viable option in applications where flexibility and safety outweigh efficiency considerations.

3.10 Blood Irradiators

Irradiation of donated blood is routinely performed to prevent transfusion-associated graft-versus-host disease (TA-GvHD), a potentially fatal complication caused by the proliferation of donor lymphocytes in immunocompromised recipients. Historically, this process has been carried out using cabinet-style irradiators containing cesium-137 radioactive sources. In recent years, there has been a significant shift toward the adoption of electrically generated X-ray systems, driven by safety, security, and regulatory considerations associated with radioactive materials. Modern low energy X-ray (LEX) irradiators provide comparable dose delivery and treatment effectiveness while eliminating the need for isotope handling, storage, and disposal. As a result, many healthcare facilities have transitioned to compact, self-shielded X-ray units available from multiple commercial vendors. Similar efforts are underway to replace radionuclide-based systems in research environments, including small animal irradiation and cellular studies, further supporting the broader adoption of X-ray-based technologies in both clinical and laboratory settings.

3.11 Wide Area X-ray Irradiators

A recent advancement in low energy X-ray (LEX) technology is the development of wide-area irradiation systems derived from industrial low energy electron beam (LEEB) platforms. In these systems, conventional sealed X-ray tubes are replaced with larger, continuously pumped vacuum chambers, enabling significantly higher beam power at comparable accelerating voltages (typically up to 300 keV). This design allows for greater X-ray output and improved processing throughput while maintaining the benefits of low-energy operation, including relatively compact and potentially self-shielded configurations.

The increased power and scalable geometry of wide-area systems expand the range of viable in-house irradiation applications. These include sterilization of medical devices, bioburden reduction in pharmaceutical products, disinfestation of fresh produce, and high-volume cannabis remediation[12]. By enabling higher throughput and continuous processing, these systems offer a practical alternative to both traditional cabinet-style X-ray units and larger, high-energy irradiation facilities, supporting decentralized and integrated processing within industrial environments.

4. LEEB & MEEB as an Alternative to Ethylene Oxide (EO)

High energy electron beam (HEEB) and high energy X-ray (HEX) systems are generally best suited for bulk irradiation applications, particularly pallet-scale processing where high penetration and uniform dose delivery through large, dense loads is required. In contrast, low energy electron beam (LEEB) and medium energy electron beam (MEEB) technologies enable a more targeted and customized approach to irradiation. Their ability to precisely control penetration depth and dose distribution allows treatment to be confined to specific regions of a product, rather than uniformly irradiating an entire packaged volume.

This capability is particularly relevant in the context of replacing ethylene oxide (EO) sterilization, where concerns may arise related to material compatibility, functional integrity, or sensitivity of certain product components. LEEB and MEEB systems can mitigate these concerns by selectively treating only the functional or exposed portions of a product, while avoiding unnecessary exposure of surrounding materials. This is especially advantageous for complex assemblies, multi-material devices, or products incorporating sensitive components such as polymers, adhesives, or embedded electronics.

By enabling irradiation of the product itself without requiring treatment of secondary packaging or shipping materials, LEEB and MEEB systems can maintain throughput levels comparable to bulk processing methods. This targeted approach supports efficient inline or near-line integration into manufacturing workflows, while expanding the range of products that can be transitioned away from EO-based sterilization processes.

4.1 Microbial Differences Between LEEB, MEEB, and HEEB

The fundamental mechanism of microbial inactivation is consistent across low, medium, and high energy electron beam systems. The energy required to create an ion pair in biological material is on the order of ~100 eV, which is several orders of magnitude lower than the initial energies of even the lowest electron beams considered in this work. As a result, a single incident electron is capable of generating a cascade of ionization events as it slows within the target material, leading to DNA damage and microbial inactivation. In this respect, the biological effect of electron beam irradiation is essentially independent of initial beam energy, provided that an equivalent absorbed dose is delivered.

The primary distinction between LEEB, MEEB, and HEEB systems therefore lies not in the mechanism of microbial inactivation, but in the spatial distribution of dose within the product. Lower energy systems exhibit significantly reduced penetration depth, resulting in highly surface-biased dose profiles.
As energy increases, penetration depth increases accordingly, enabling more volumetric and uniform dose. Consequently, accurate dose mapping becomes essential across all energy regimes to ensure that the minimum required dose is achieved throughout the target material, regardless of beam type.

At very low initial energies, on the order of approximately 80 keV, Monte Carlo simulations indicate a potential increase in biological effectiveness of up to ~20% compared to higher-energy electrons. However, as previously stated, the penetration depth at these energies is extremely limited—typically on the order of tens of micrometers in water-equivalent material. In practical industrial applications, such shallow penetration means that this effect is unlikely to be observable in routine processing or standard dose mapping procedures. Accordingly, differences in microbial inactivation across LEEB, MEEB, and HEEB systems are primarily governed by dosimetric distribution rather than intrinsic differences in radiation chemistry or biological response.

5. Future Perspectives

The continued development of low-, medium-, and high-energy electron beam and X-ray technologies is expected to be driven by increasing demand for flexible, scalable, and sustainable alternatives to conventional chemical and isotope-based processes. In particular, low and medium energy systems are likely to see accelerated adoption as industries seek to decentralize sterilization and material processing, expanding beyond large centralized irradiation facilities toward in-line and on-demand treatment solutions. Advances in accelerator design, including improved efficiency, compact RF structures, and more robust self-shielded configurations, are expected to further reduce installation complexity and expand the range of economically viable applications.

A key area of future growth lies in the integration of irradiation systems into fully automated production environments. This includes real-time dose monitoring, advanced beam scanning and shaping technologies, and closed-loop process control systems capable of adjusting beam parameters dynamically based on product geometry and material response. In parallel, developments in wide-area low energy X-ray systems and high-power electron sources are expected to enhance throughput while maintaining precise dose control, enabling irradiation to become a fully embedded unit operation in pharmaceutical, medical device, food, and advanced materials manufacturing.

Emerging applications in biotechnology, cell therapy, and functional materials are also likely to benefit from the unique capabilities of low-energy electron irradiation, particularly where selective inactivation or modification of biological structures is required without extensive thermal or chemical damage. As regulatory frameworks continue to evolve in support of non-chemical sterilization and sustainable manufacturing practices, electron beam and X-ray technologies are expected to play an increasingly central role in next-generation industrial processing platforms.

6. Conclusion

Low-, medium-, and high-energy electron beam and X-ray technologies collectively provide a versatile and scalable toolkit for industrial irradiation across a wide range of applications. While high-energy systems remain essential for bulk and pallet-level processing, low- and medium-energy technologies offer significant advantages in terms of flexibility, integration potential, and targeted dose delivery. These systems enable precise control of penetration depth and dose distribution, allowing tailored solutions for sensitive materials, complex product geometries, and inline manufacturing environments.

Across applications including polymer modification, sterilization, food treatment, medical device processing, and advanced manufacturing, these technologies continue to expand their industrial relevance. Their ability to replace or complement traditional chemical and isotope-based processes further enhances their strategic importance in a landscape increasingly focused on safety, sustainability, and process efficiency. As technology continues to evolve, electron beam and X-ray systems are expected to become even more deeply embedded in modern manufacturing and healthcare infrastructure, supporting a broad range of high-value industrial applications.

7. Resources

As in many industries, providers of electron beam and X-ray systems and associated accessories and infrastructure are constantly changing. For an up-to-date list see the iia Electron Beam and X-ray Supplier Database https://iiaglobal.com/iia-information-hub/eb-x-systems-and-suppliers/.

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