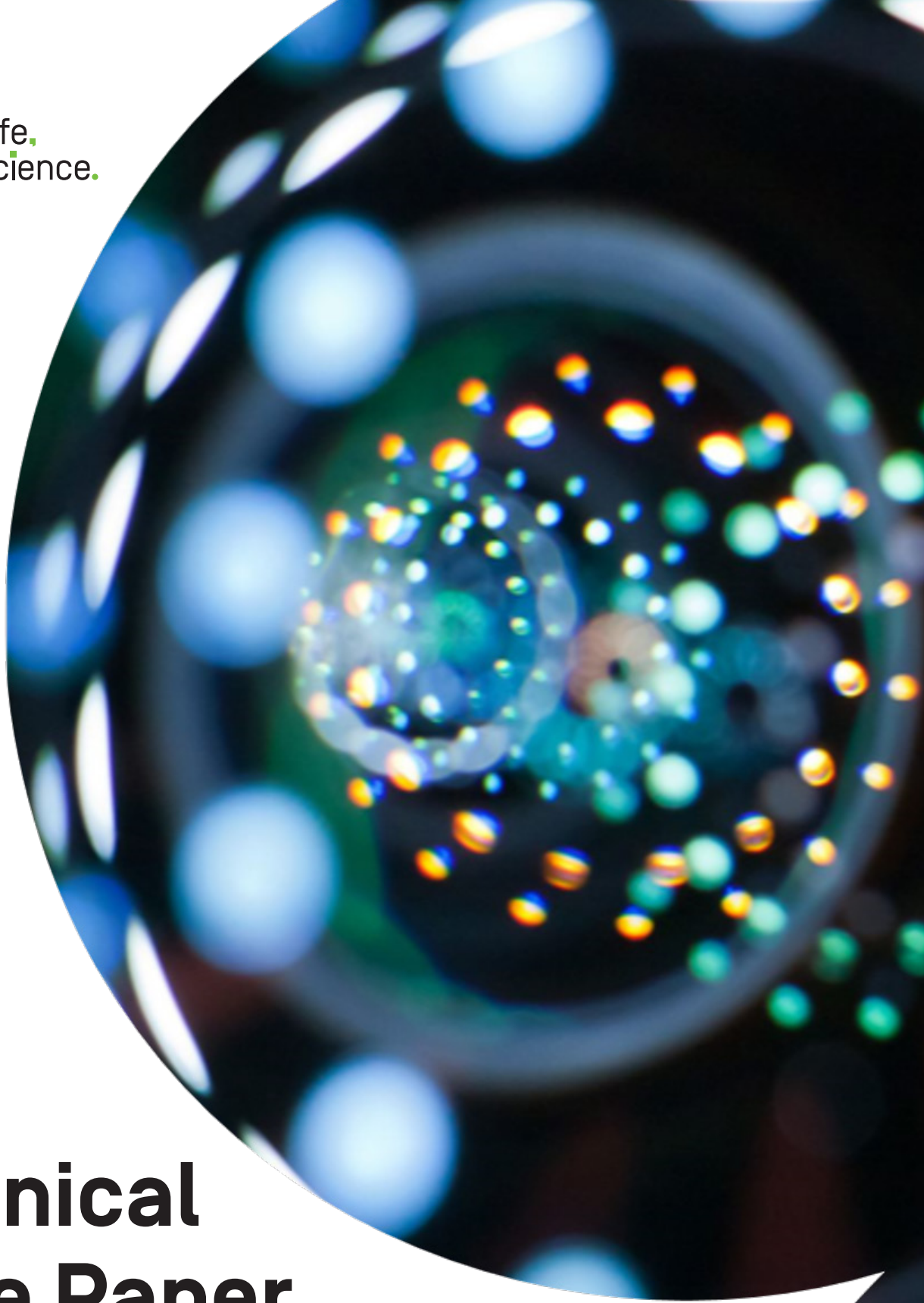




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Technical White Paper

**High-Energy Electron-Beam Technology
for Advanced Polymer Engineering**

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specialized in E-beam and X-ray irradiation of polymers

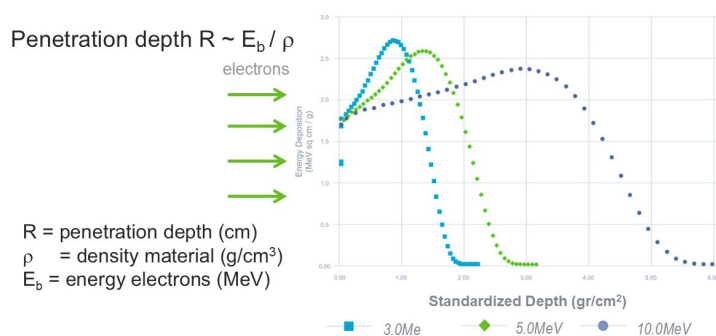
High-Energy Electron-Beam Technology for Advanced Polymer Engineering

Unlocking Bulk Material Modification, Scalable Processing, and Next-Generation Polymer Architectures

Electron-beam irradiation is a well-established technology in materials science with a broad range of industrial applications. Within the polymer and materials community, it is primarily associated with surface modification, such as the curing of thin layers, coatings, or highly pigmented inks as an alternative to UV curing. In polymer manufacturing, E-beam irradiation is also used in niche applications. A prominent example is the pre crosslinking of rubber compounds in tire manufacturing, where surface irradiation creates a hardened skin that improves shape stability and morphology during subsequent vulcanization.

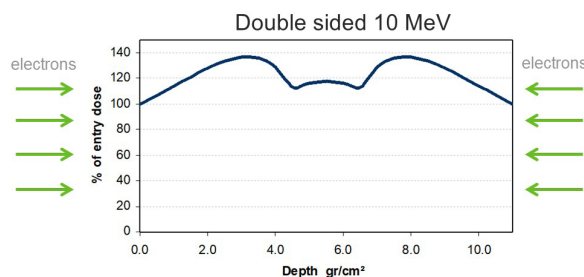
What remains far less widespread is the application of E-beam irradiation to **bulk material processing**, where electrons trigger chemical reactions deep inside polymeric objects. Recent technological advances in accelerator design, particularly the shift from kilovolt to megavolt scale acceleration voltages, have fundamentally expanded the application space of E-beam irradiation. Modern high energy E-beam accelerators operate at acceleration voltages in the megavolt range. Because the penetration depth of electrons in matter scales approximately linearly with acceleration voltage, this development has increased penetration depths from the sub millimeter range to **several centimeters** - and, under optimized conditions, up to **one decimeter**.

For an electron accelerator operating at 10 MeV, the penetration depth in a material with a density of 1 g/cm³ is approximately 5 cm. This depth scales inversely with material density and remains

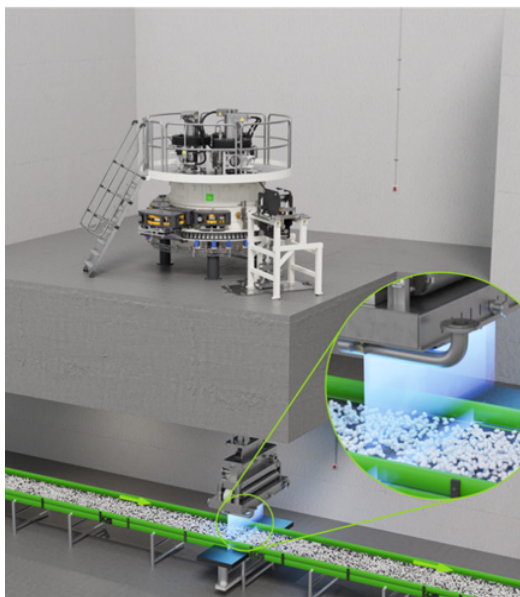


independent of color or chemical composition. As a result, E-beam irradiation is uniquely suited for processing highly pigmented systems as well as complex composite materials containing fibers, fillers, and additives.

Beyond deeper penetration, high-energy electrons also deliver **superior dose homogeneity** compared to lower-energy systems. This uniformity can be further enhanced using double-sided irradiation configurations, achieving dose variations below 20% across material thicknesses of up to one decimeter—an essential requirement for consistent bulk modification.



While acceleration voltage defines the maximum treatable thickness, beam power is the key driver of industrial productivity. Over recent decades, continuous technological advancements have increased accelerator power from 20–50 kW to **beyond 500 kW**. Since beam power directly determines throughput (mass per unit time), modern high-power systems now enable the **processing of up to 20-70 tons of material per hour**.



This combination of high penetration depth and high throughput fundamentally reshapes the industrial potential of E-beam technology. It unlocks applications where E-beam-induced chemistry was previously not considered economically viable at scale. Beyond established uses such as crosslinking of cables, tubes, and composites, a rapidly emerging field is the E-beam-assisted synthesis of engineered polymers with tailored functionalities and advanced architectures.

In this context, modern E-beam accelerators can be regarded as **highly efficient, continuous chemical reactors**, capable of processing a wide variety of

material formats—including powders, pellets, molten streams, liquids, extruded profiles, and fully shaped components.

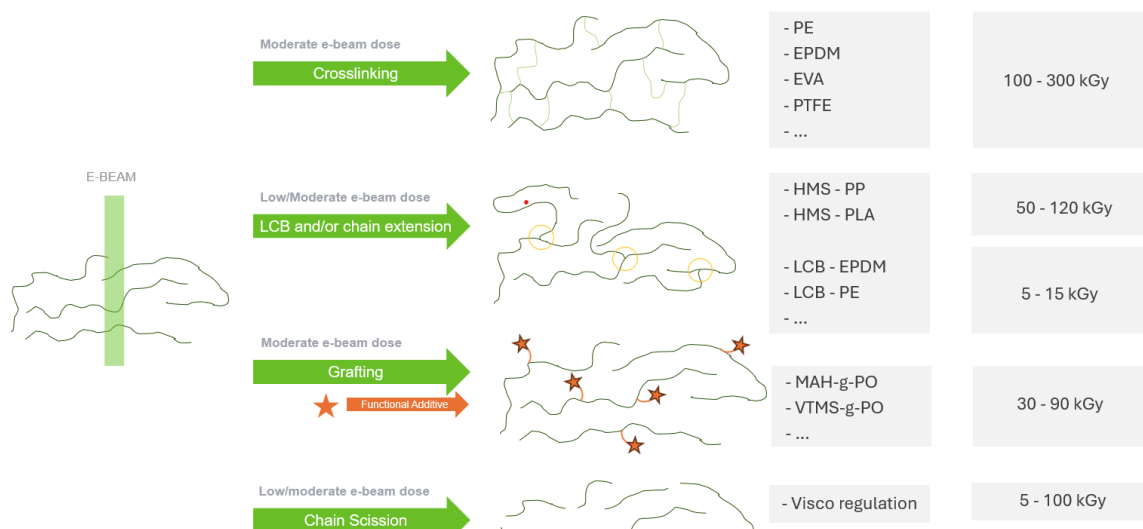
What happens when irradiating a polymer with electrons?

When a polymer is exposed to high-energy electrons, reactive radicals are generated primarily through homolytic bond scission. Bonds with the lowest dissociation energies are preferentially cleaved, leading to the formation of reactive species that can initiate a wide spectrum of chemical transformations.

Traditionally, such bulk modifications rely on thermal radical initiators (e.g., peroxides) incorporated into the polymer matrix and activated by heat. However, these additives remain in the final material, raising concerns related to health, safety, and environmental impact throughout production, processing, and end use.

E-beam initiation eliminates the need for such chemicals, offering a **residue-free alternative**, which is particularly advantageous for sensitive applications such as food contact materials. At the same time, it enables access to new performance levels by facilitating increasing the strength of composite materials, grafting molecules to improve adhesion, creating long-chain branching for the production of lighter foams, and enhancing the mechanical properties of recycled plastics.

Depending on the polymer system, formulation, applied dose [kGy], dose rate [kGy/s], and processing conditions [temperature, atmosphere], E-beam irradiation can induce a broad range of reactions, including curing, long-chain branching, chain extension, grafting, and controlled chain scission.



At very high doses, polymers as well as organic compounds undergo pyrolysis or even complete mineralization. This capability is now being actively explored for the degradation of persistent pollutants such as PFAS in contaminated water, sludge, and soil.

Why use E-beam instead of conventional chemical approaches?

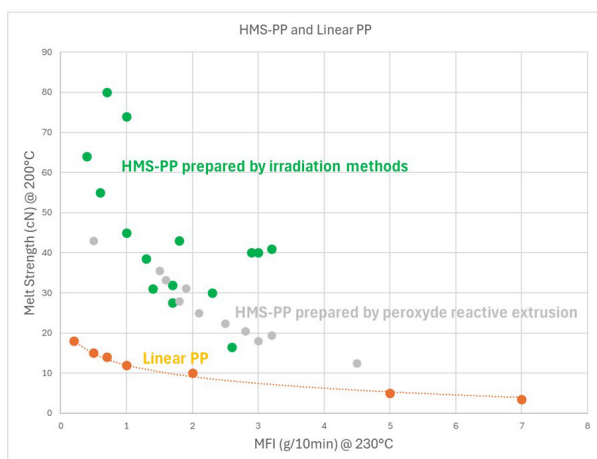
A key differentiator of E-beam technology is the **decoupling of radical formation from temperature**. Unlike peroxide-based systems, radicals can be generated at virtually any desired temperature, significantly expanding the process window and minimizing undesired side reactions such as thermo-oxidation and uncontrolled chain scission.

In conventional thermal processes, radical generation is inherently non-uniform due to local temperature gradients and fluctuations in initiator concentration. Local concentration spikes—sometimes exceeding 1000% of the average—are not uncommon in reactive extrusion, leading to variability in material properties and undesired effects such as premature gelation.

In contrast, E-beam irradiation provides **exceptionally uniform radical generation**, directly governed by dose distribution. Well-designed systems achieve dose variations below 20%, enabling a level of control that is unattainable with traditional approaches.

This high degree of control opens the door to polymer architectures that are difficult—or impossible—to produce using conventional chemical processes. For example, high grafting levels of functional vinylic monomers [e.g., maleic anhydride, silanes] onto polyolefins, polyamides, or fluoropolymers can be achieved with significantly reduced side reactions such as gelation, thermal degradation, and homopolymerization.

A particularly illustrative case is the transformation of linear polypropylene (PP) into long-chain branched polypropylene (LCB-PP). Linear PP suffers from low melt strength, limiting its use in demanding processes such as foaming, thermoforming, and film blowing. The introduction of long-chain branches increases chain entanglement, resulting in **high melt strength (HMS)** and improved process stability.



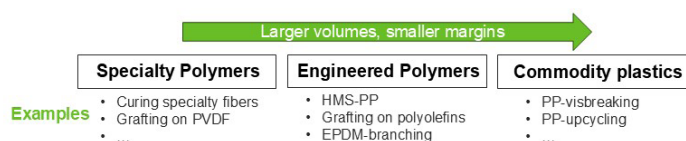
The long-chain branching reaction is a complex multistep process in which the generated radicals can lead to both chain scission and recombination of polymer chains.

If the reaction is not well balanced, excessive chain scission results in reduced melt strength, while excessive recombination leads to crosslinking and undesired gelation, rendering the material unsuitable for subsequent processing steps such as film blowing or foaming.

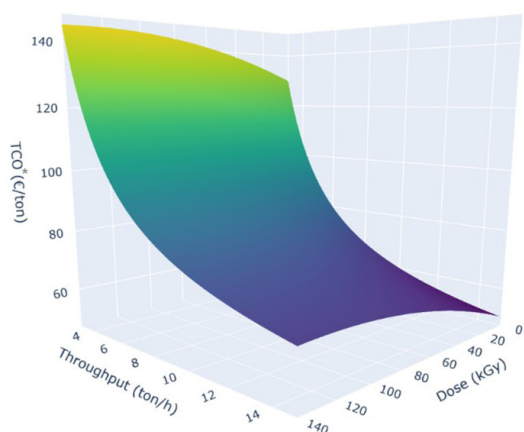
From a macroscopic perspective, the objective is to obtain a polymer with relatively low melt viscosity [i.e., a high melt flow index, MFI] to ensure processability, while maintaining high melt strength to prevent collapse in the molten state until the polymer is cooled and solidified. It has been demonstrated in both academic and patent literature that, compared to reactive extrusion, E-beam-induced reactions allow much better control over polymer architecture, resulting in improved rheological properties.

Is this approach cost-competitive and industrially scalable?

E-beam-assisted polymer modification has been used industrially for over two decades, initially in low-volume, specialty polymer applications. Historically, broader adoption was constrained by low beam power and high capital costs, limiting its viability for large-scale, cost-sensitive markets. Recent advances in high-power accelerator technology have fundamentally changed this landscape. Today, E-beam processing supports high-throughput operations (5–70 tons per hour), with production costs falling below €100 per ton. This makes the technology increasingly viable not only for engineered polymers but, in some cases, also for commodity plastics.



The irradiation cost per ton is primarily driven by two factors: the required irradiation dose [which determines energy consumption] and system throughput. For low-volume or pilot-scale production, irradiation is typically outsourced to specialized service providers. This approach offers flexibility without upfront investment, though costs generally start above €1,000 per ton. As volumes increase, the cost per ton decreases, often dropping below €200 per ton.



*for 80%-line capacity on an integrated IBA Rhodotron TT1000 640 kW equipment

For some applications requiring relatively low doses and running at very high throughputs, such as branching of EPDM rubber to improve green strength, costs can be reduced even further, in some cases to below €20 per ton.

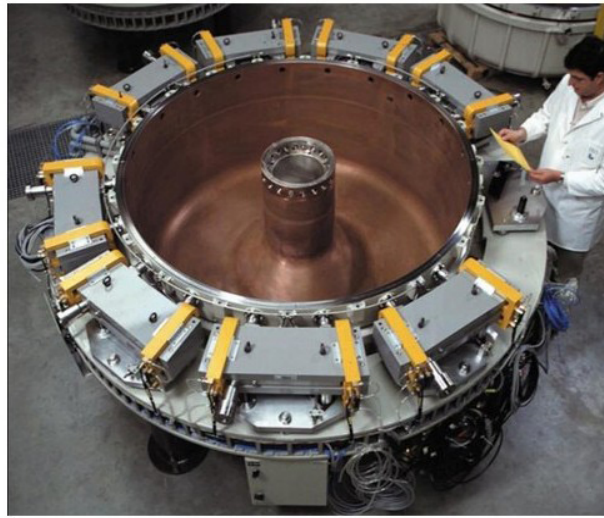
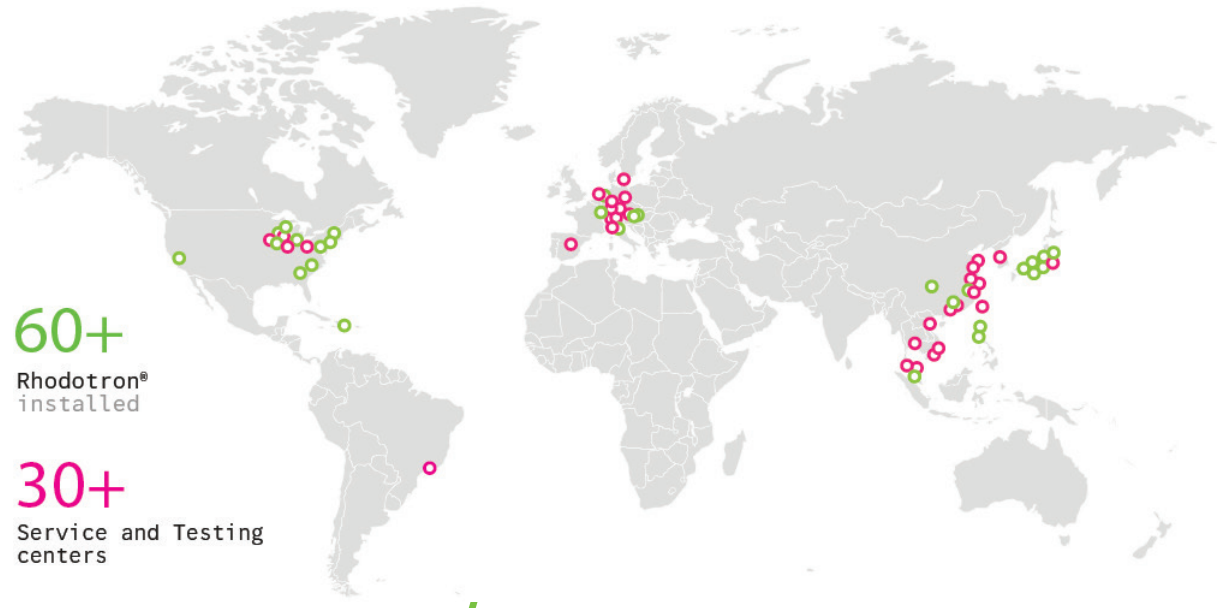
Despite these significant advancements, E-beam processing is still often perceived as an expensive niche technology - an outdated view that no longer reflects its current industrial capabilities.

What does the future hold?

As the gap between polymer chemistry and irradiation technology continues to close, new applications, synergies, and business opportunities are rapidly emerging. Beyond the industrialization of established processes, innovations such as micro-pulse E-beaming and variable dose scanning are opening new dimensions in process control and material design. From a polymer chemistry perspective, modern E-beam accelerators can be seen as **highly tunable, continuous chemical reactors**, offering precise control over where radicals are generated, in what quantity, at what rate, and under which thermal conditions. This level of control significantly expands the available process toolbox and positions E-beam technology as a key enabler for the next generation of high-performance, engineered polymer materials.

To accelerate the growth of these emerging polymer and advanced material applications, IBA is not only developing and integrating new dedicated E-beam accelerators, but also actively supporting material chemistry R&D. This is achieved through close collaboration with the polymer industry and a broad network of E-beam service and testing centers across Europe, the United States, and Asia.

Rhodotron® installed base 2025



ABOUT IBA

IBA (Ion Beam Applications) is a global medical technology company focused on bringing integrated and innovative solutions for the diagnosis and treatment of cancer. The company's expertise lies in the development of next-generation proton therapy technologies and radiopharmaceuticals that provide oncology care providers with premium quality services and equipment, including IBA's leading fully-integrated IntegraLab® system.

The company also offers irradiation and ionization solutions to improve the hygiene and safety of everyday life.

IBA, a Belgian company, is listed on the Pan-European stock exchange EURONEXT.

ABOUT IBA INDUSTRIAL

IBA INDUSTRIAL is the world leader in electron and proton accelerators for industrial applications. Its unique E-beam, X-ray and Proton treatment solutions are used across the world.

Today, IBA Industrial brings to the market a new value proposition, an experience it lives with its Customers through the whole journey. This experience is called BEYOND™, a commitment to go above any expectations.

Its end-to-end solutions are available for all meaningful applications such as medical devices sterilization, food pasteurization, property enhancement for various materials, etc

IBA Industrial cares about its Customers from start to infinity. It accompanies them in each step of the project from site planning and optimization, engineering, and integration of all operational sub-systems to assistance in operation and beyond.



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