Applications of Accelerators: Industrial Applications of Particle beams

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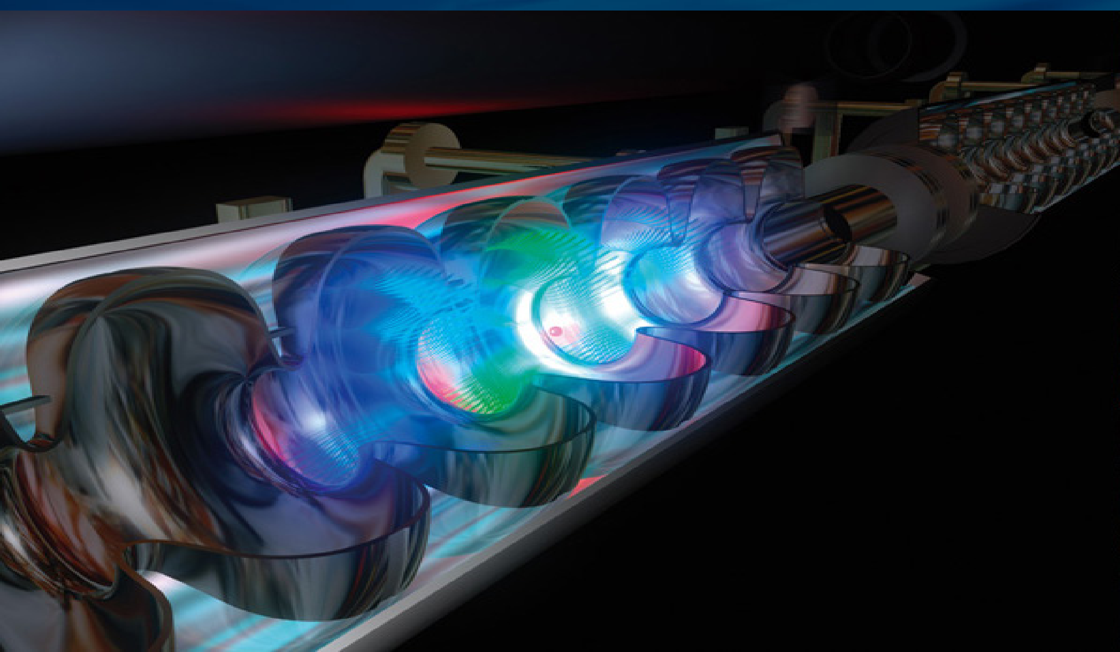
Images courtesy of Zimek Zbigniew, ICNT, and Sammi Hanna, SLAC

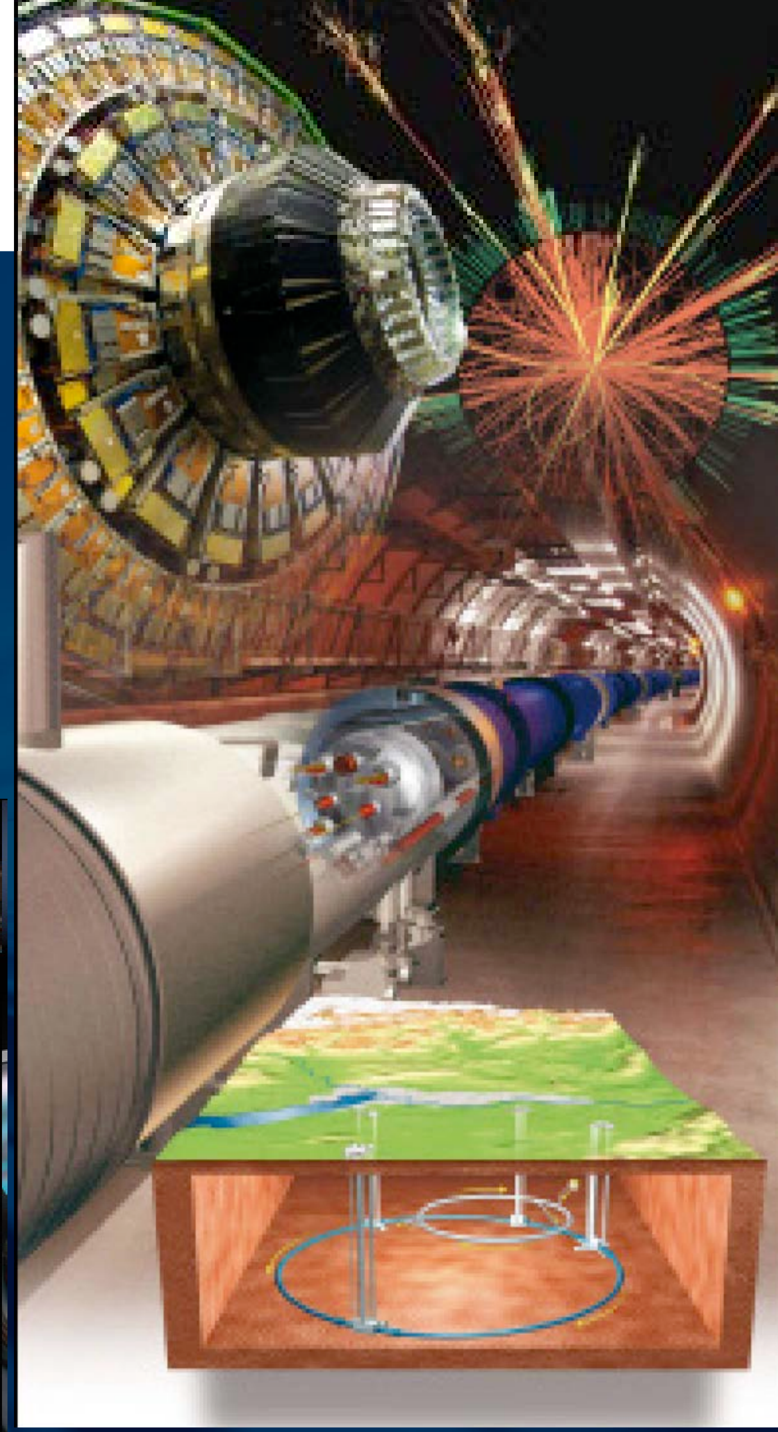
Accelerators for Particle Physics

In order to study the Higgs boson and new physics at the Terascale exciting new accelerators with higher energy and more luminosity are required.

The UK is playing a lead role in

- Upgrading the LHC
- Designing the next linear collider
- Neutrino factories





Accelerators for probing matter

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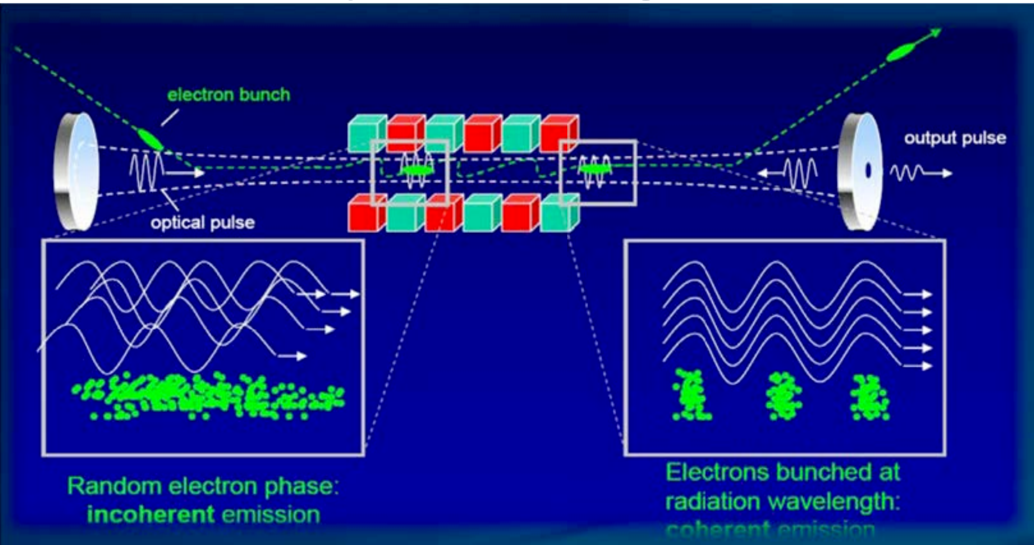
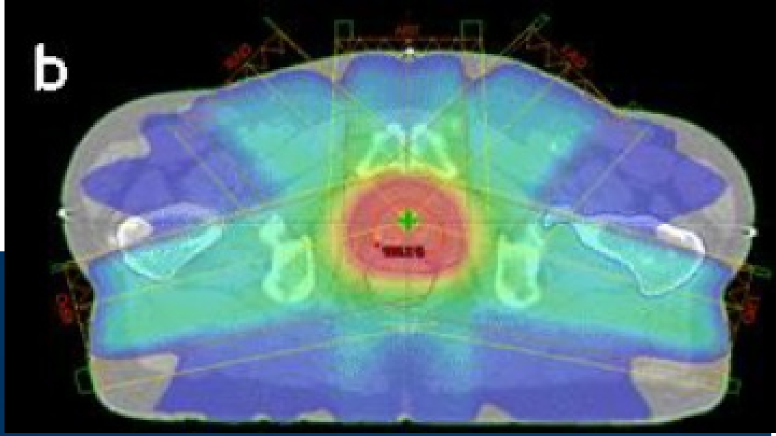


New X-ray and neutron sources are needed to study biology, chemistry and new materials

The UK is playing a lead role in

- ISIS Spallation source
- CLARA – UK FEL test facility
- ALICE – THz and IR source
- DIAMOND – The UK's light source

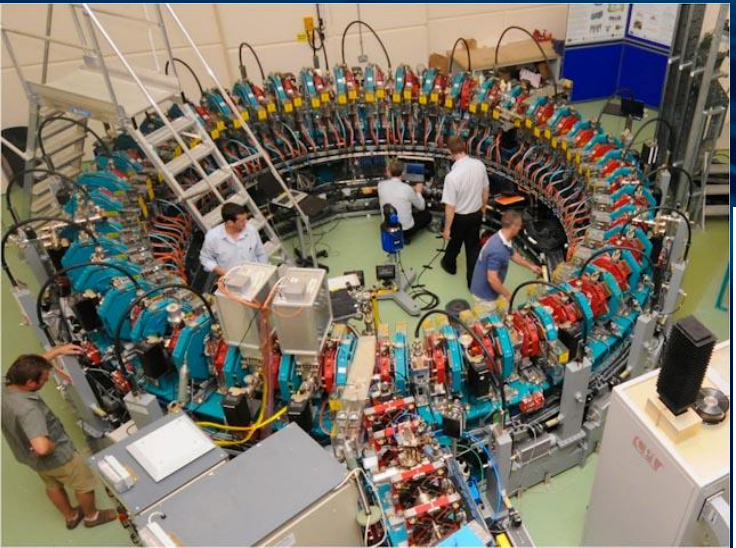
Accelerators for Medical, Energy and Security

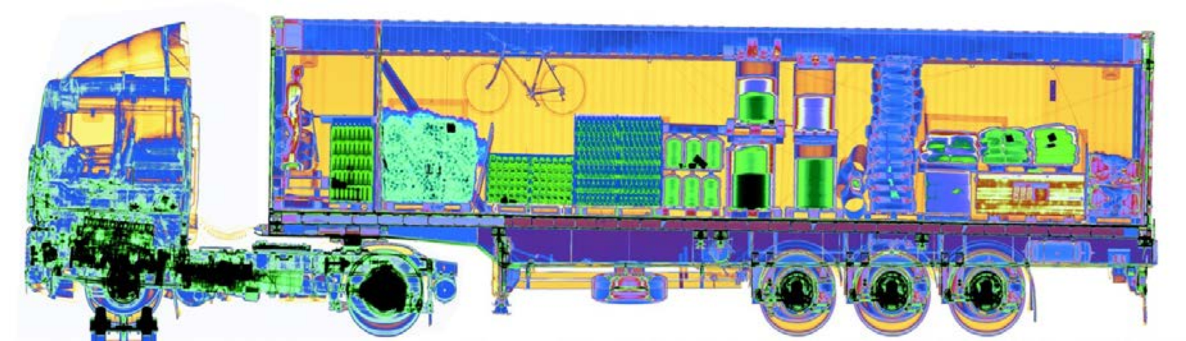


Accelerators can be used to produce X-rays, electrons and hadrons for

- Treatment of cancer with hadrons
- Radiotherapy
- Sub-critical nuclear reactors
- Scanning of cargo

The UK is developing a new generation of particle accelerators to meet the needs of these applications





Applications of accelerators

- Medical (PET isotopes, radiotherapy)
- Energy (ADSR)
- Light Sources (Synchrotrons and FELs)
- Spallation Sources (Produce neutrons)
- Industrial Applications
- Security (Cargo screening)

5 Main Industrial Applications

- Processing of Polymers (cross-linking, curing, gemstone colouring) – To make them stronger, heat resistance, heat shrinkable, dry faster or change the colour.
- Sterilisation – Use of electrons or X-rays to kill pathogens or prevent undesirable changes.
- Non-destructive testing (NDT) – Inspection of components for flaws or hidden features. High energy X-rays are need for thick components.
- Ion implanting in chip fabrication – To dope semiconductors to alter near surface properties by placing ions at specific locations and depths.
- Watewater and Flue gas treatment – To remove contaminants or bye products of other processes.

Particle Accelerators in the UK

Particle accelerators can have different sizes and shapes. Some are very big and require their own building, like Diamond, ISIS or ALICE but others are much smaller, small enough to fit in an hospital.

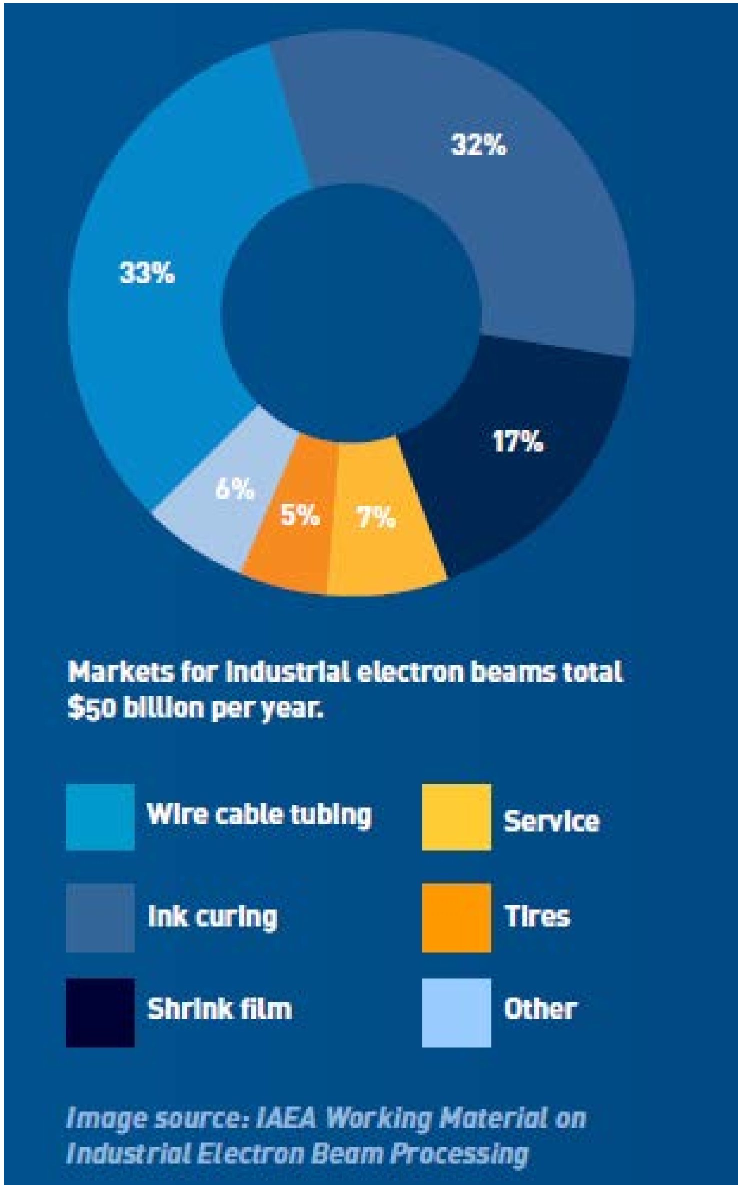
In total there are more than 150 particle accelerators in the UK, and 20,000 workdwide. Every major city, every major hospital has at least a few.

The map on the left shows most locations in the UK where there is a particle accelerator.

Roughly half of the 20,000 are medical and the other half are industrial.

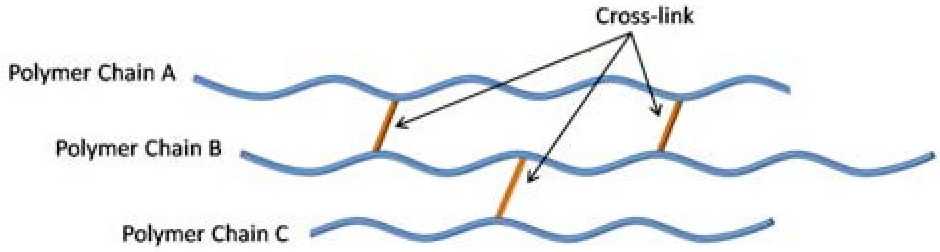
Market for Industrial accelerators

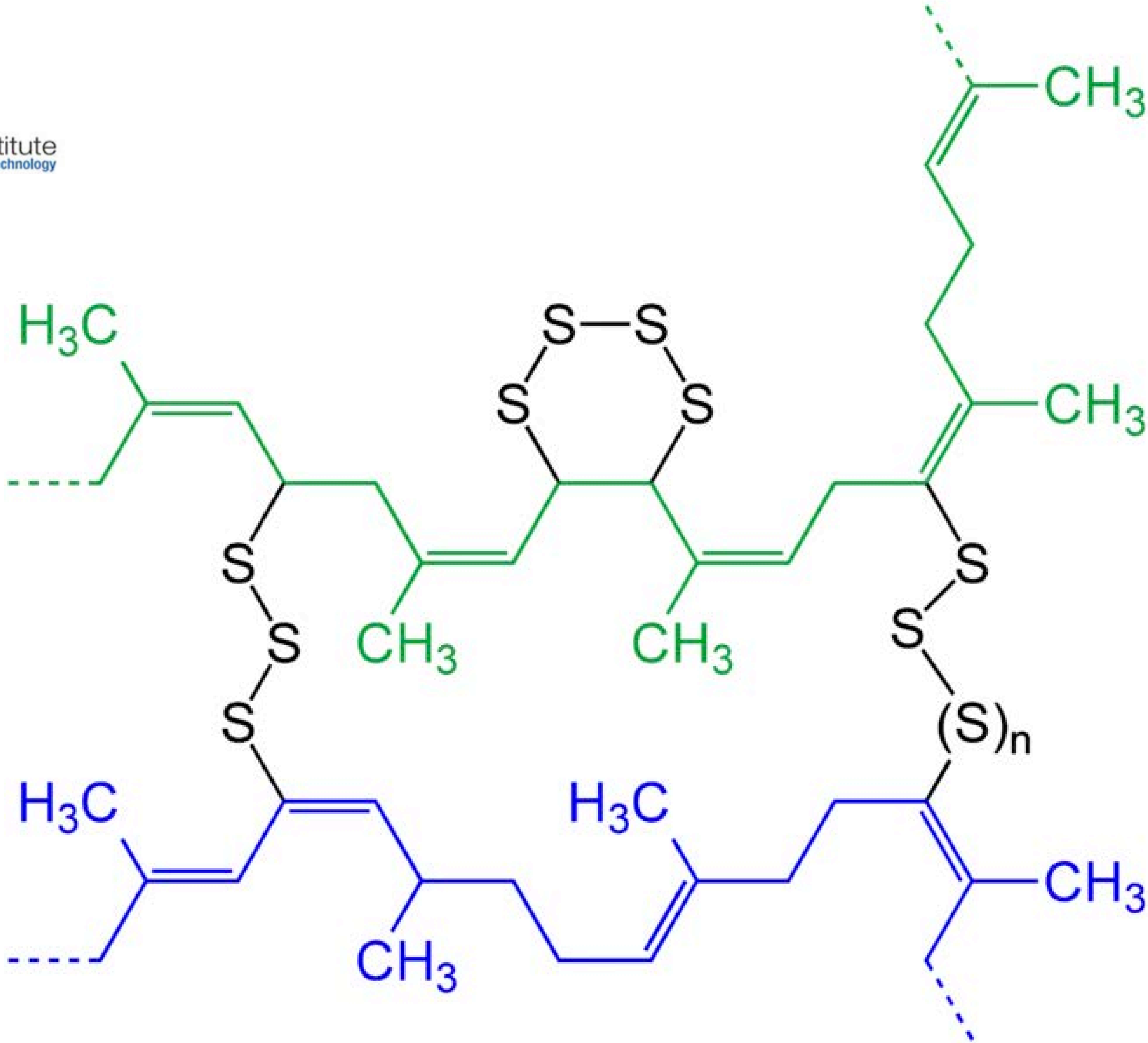
- There are around 20,000 accelerators in operation worldwide. 10,000 of these are for industrial applications. Around 900 accelerators are sold per year for industrial applications in a market worth $50 Billion per year.



Cross-linking

- Cross-linking is the process of bonding polymer strings together.
- They can be covalent bonds or ionic bonds. "Polymer chains" can refer to synthetic polymers or natural polymers (such as proteins).
- The effect of this is to make the polymer stronger and heat resistant. This is often used to make cable insulation that doesn’t melt.
- It can also make them insoluble.
- It can also be used to make the polymer shrink when heat is applied. This process is used to wrap most chickens, turkeys, pizza etc as well as lots of electronics and tamper proof packaging.





- [Vulcanization]() is an example of cross-linking. Schematic presentation of two "polymer chains" (**blue** and **green**) cross-linked after the [vulcanization]() of natural rubber with [sulfur]() (n = 0, 1, 2, 3 …).

Reasons for Cross-linking

- Thermal: resistance to temperature, aging, low temperature impact, etc.
- Mechanical: tensile strength, modulus, abrasion resistance, pressure rating, creep resistance, etc.
- Chemical: stress crack resistance, etc.
- Other: heat shrink memory properties, positive temperature coefficient, etc.

Cross-linking

- Heat-shrinkable film—commonly known as shrink wrap—is made of polyethylene plastic. The plastic molecules, called polymers, are long chains of carbon atoms strung together. Each carbon atom also connects with two hydrogen atoms, leaving it no room to bond with anything else.
- The fully saturated carbon becomes chemically inert, if you heat it to the boiling point of water, it will melt. In the case of electron-beam irradiation, highly energetic electrons strike at or near the carbon-hydrogen bonds in target molecules, and give up enough energy to the molecules to break some of the bonds, releasing hydrogen, and leaving the molecules with excited carbon atoms (free radicals). When this process occurs at two adjacent molecules or nearby sites, excited carbon atoms can release excitation energy forming a chemical bond, known as a cross-link, between them.
- When fully cross-linked, the plastic becomes elastic if you heat it to boiling temperature, but it won't melt. After electron beam treatment, the plastic is stronger and more heat resistant. It can be heated and stretched into a thin film without ripping. When cooled to room temperature, the crosslinked plastic retains its expanded shape. Place something inside it, such as a Butterball turkey, and apply heat, and the plastic shrinks back down to its original size, resulting in an air-tight wrapping.

Cross-linking

- Most car tyres are also treated with electron beams. The rubber is extruded then cross-linked bringing it into a gel state. In the gelled state the elastic polymers gain more elasticity as the chains stretch under stress. This makes the rubber tougher and helps with futher moulding.
- The high degree of control of electron beams allow the manufactures to partially cure or cross-link some parts of the tyres but not others.

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Curing

- In EB curing chemical are added to cure inks and coatings.
- The ink is made of monomers and short chain polymers that are cross-linked by the beam to solidify them instantly.
- This uses 100 times less energy that water-borne drying and as no material is evaporated there are no volatile organic compounds (VOCs)
- In addition as it isn't a thermal mean of drying it can take place at ambient temperatures which is required for most plastics and heat sensitive films.
- It is similar to UV curing but has the ability to penetrate pigments.
- A typical use is in printing cereal boxes.

Gemstone colouring

- Ionizing radiation can change the atomic structure of the gemstone's crystal lattice, which in turn alters the optical properties within it
- Certain natural gemstone colours, such as blue-to-green colours in diamonds, are the results of the exposure to natural radiation in the earth. The limited penetrating ability of these particles result in partial colouring of the diamond's surface.
- Only high-energy radiation can produce fully saturated body colours, and the sources of these types of radiation are rare in nature, which necessitates the artificial treatment by electron beams in the jewellery industry.

Other uses

- Cross-linked closed-cell polyethylene foam cushions the interior of automobile, roof liners and door panels.
- Wood-polymer composites which are stronger and moisture, mold and fungi resistant.
- Carbon-fibre composites: Curing in the mould results in shorter curing times.
- E-beams can also break down non-edible starches and cellulose to create alchohol as a biofuel without creating toxins that interfere with fermentation.
- E-beams are commonly used to change the colour of gemstones. Topaz is actually brown but e-beams give them their typical blue colour. The same process is also used on quartz, diamond, amethyst and rubellite.
- breaking down of cellulose fibers extracted from wood in order to shorten the molecules, thereby producing a raw material that can then be used to produce biodegradable detergents and diet-food substitutes

Penetration of e-beams in water

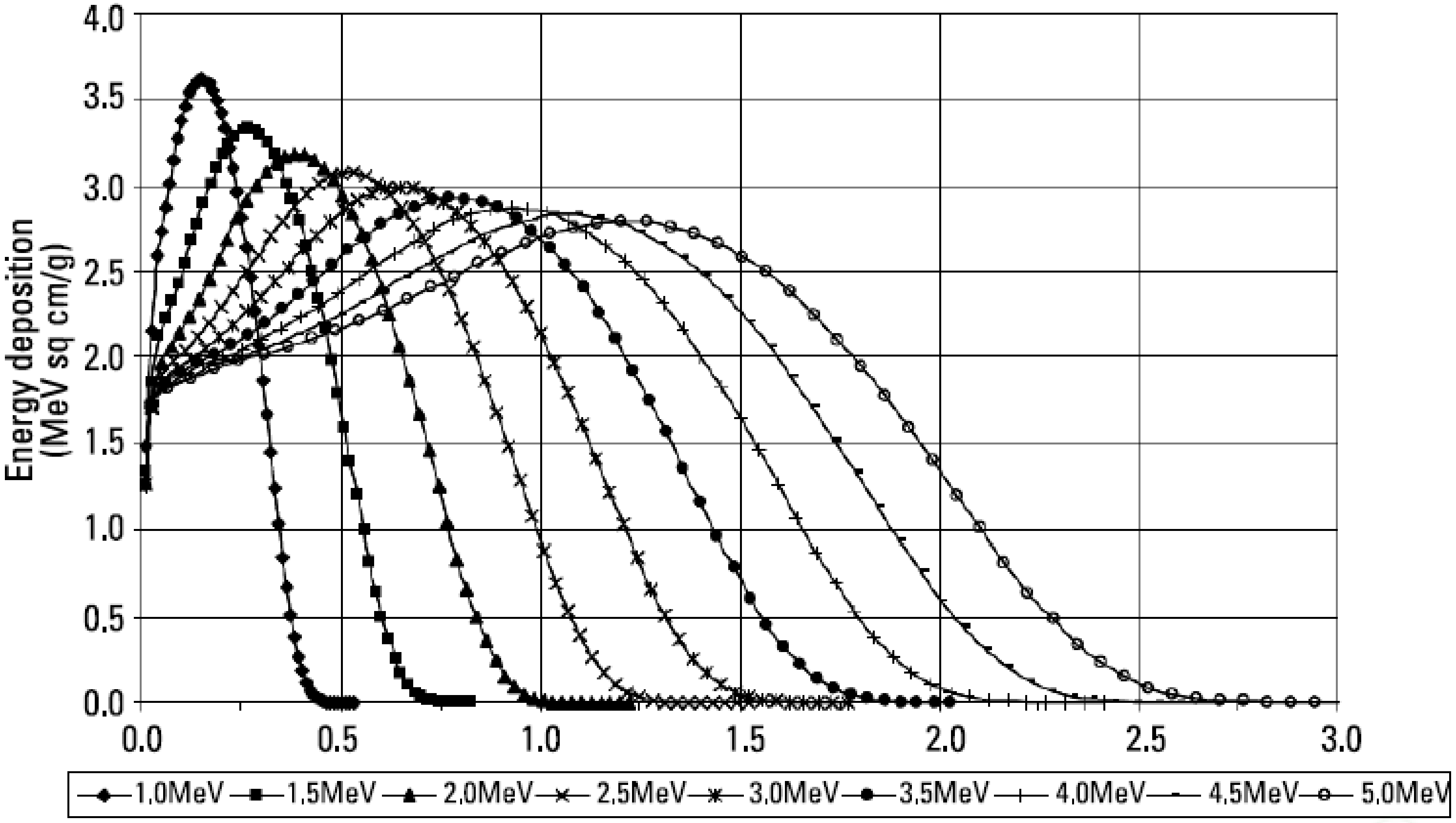
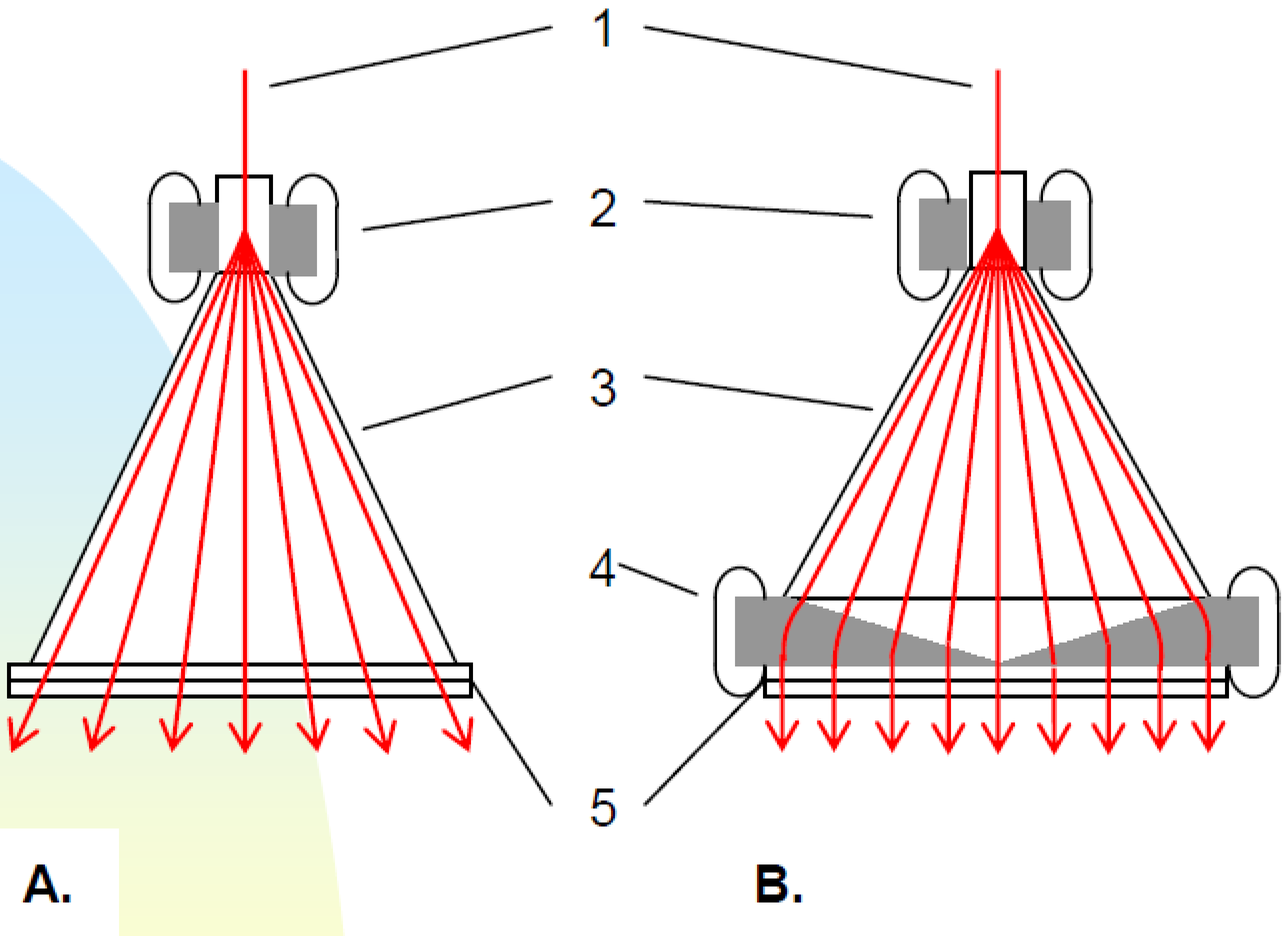


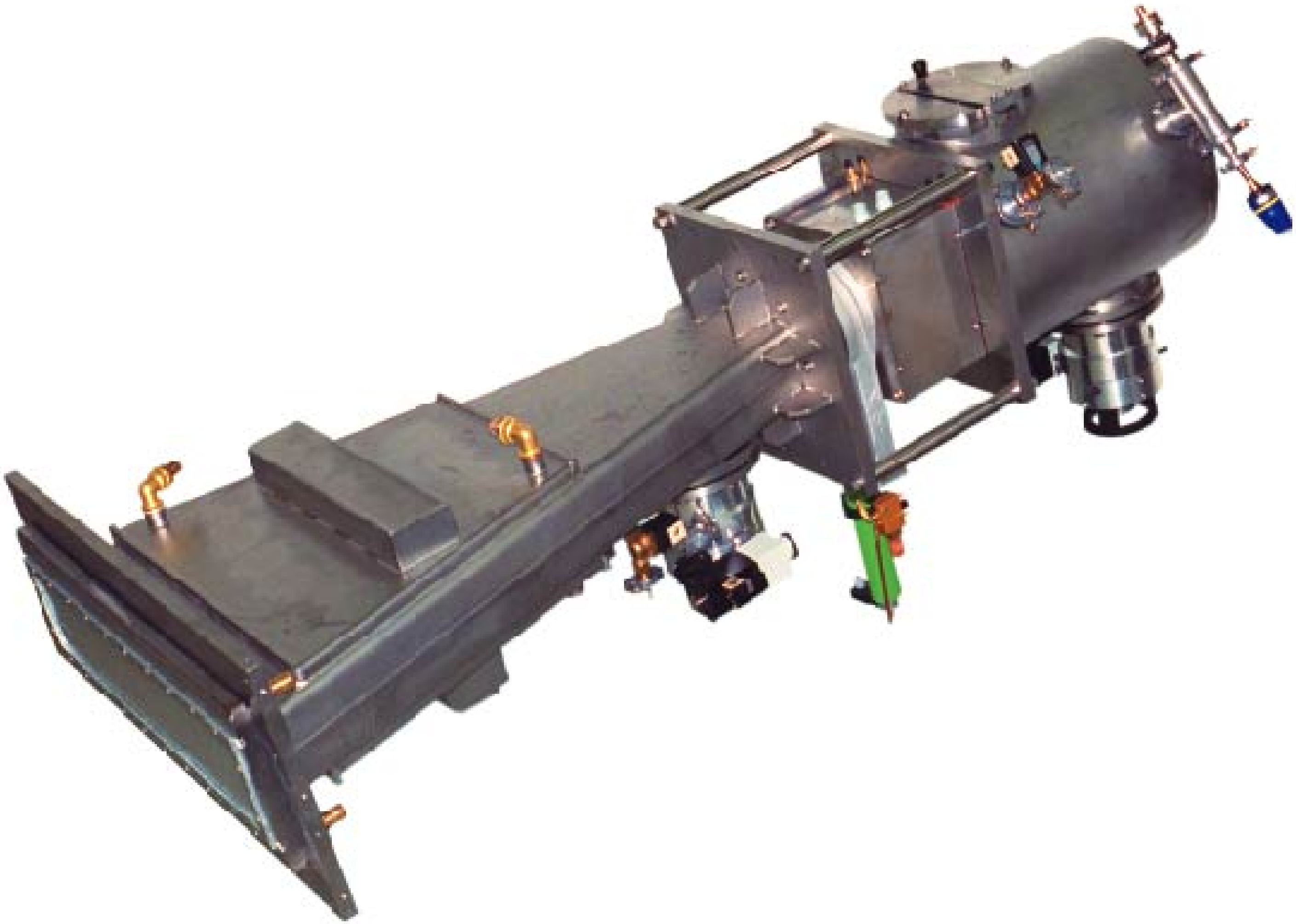
Figure 6.1 Electron beam energy deposition in centimeters of water (1 to 5 MeV) [2].



Different configuration of accelerator output device (A – triangular scanning, B – parallel beam): 1 – electron beam; 2 – scanning magnet, 3 – scanner; 4 – correction electromagnet; 5 – output foil

Image courtesy of Zimek Zbigniew, ICNT

Industrial accelerator



ESI EZ-Cure III™ Unit

Image courtesy of Zimek Zbigniew, ICNT

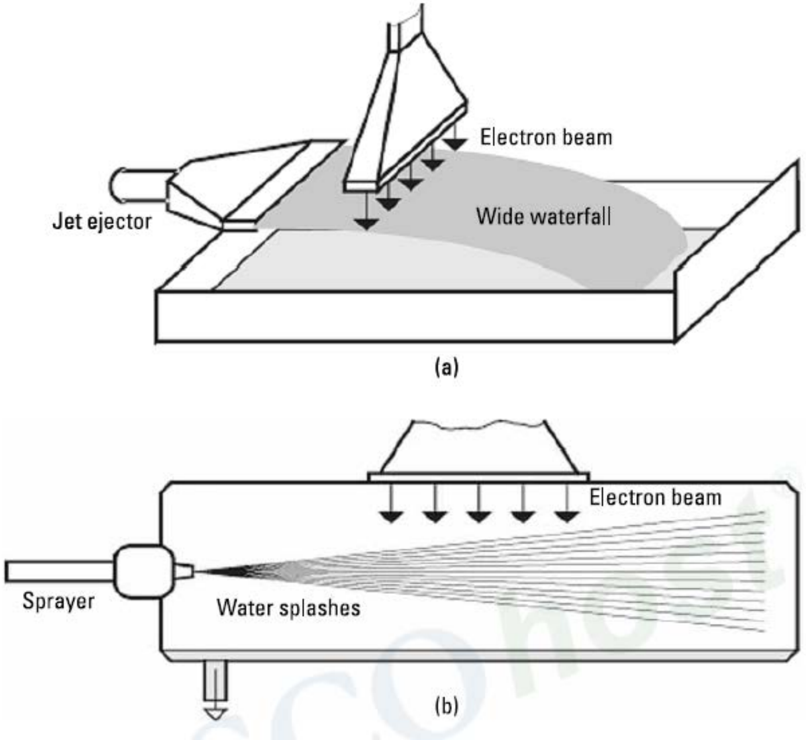
Cryovac Production Facility

State of the Art - 10 EB Units in a Row

Image courtesy of Zimek Zbigniew, ICNT

Water treatment

- Water isn't normally reactive but when treated with electron beams it produces reactive species (hydrated electrons, hydroxyl radicals and hydrogen atoms).
- These reactive species can destroy organic compounds in polluted water. This can drive both oxidising and reduction reactions at the same time.
- EB treatment is the only way to create both highly oxidising and highly reducing reactive species in equal concentrations in aqueous solutions.



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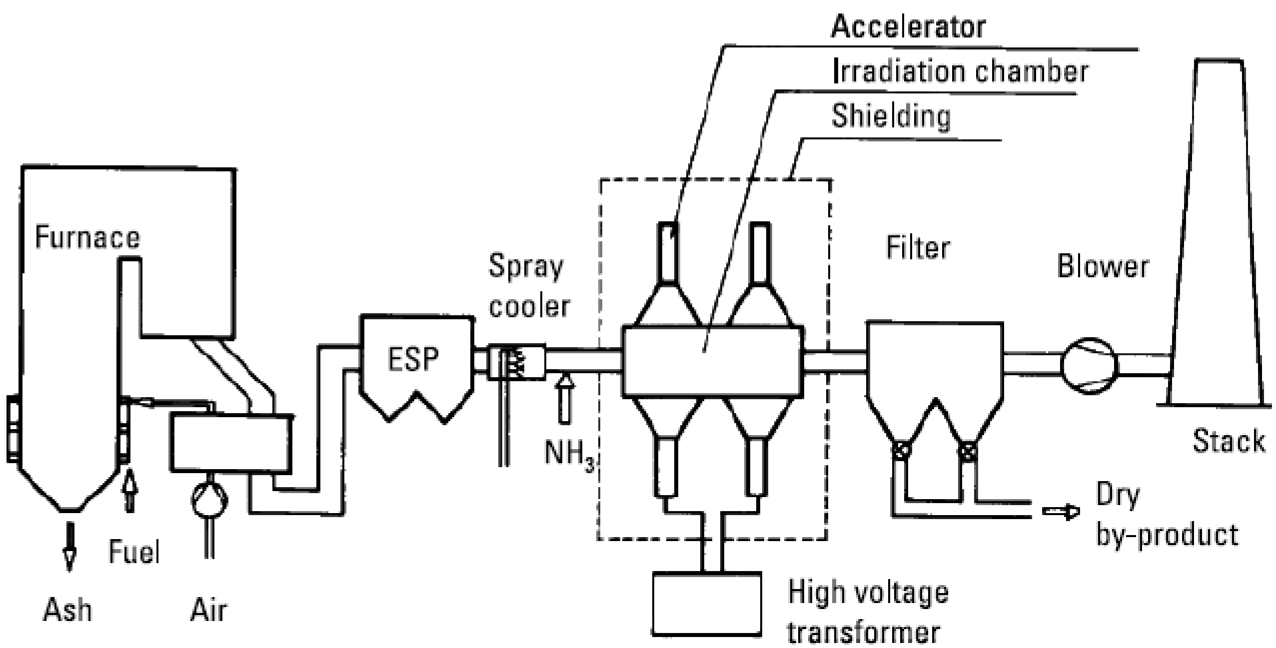
Flue gas

The EB flue gas processing is based on the formation of acid vapors under
ntrolled conditions within the power plant. These acidic gases can then be
utralized by injecting ammonia vapor to proc
um sulfate ($(NH_4)_2SO_4$) and ammonium nit
removed from the gas stream by conventional
ecipitators (ESPs) or filters. A simplified diagra
own in Figure 6.9 [21]. The proof of principle
s demonstrated by Japanese scientists in the 197
pilot and large scale facilities by researchers in Germany, Japan, Poland, Bul-
ria, China, and the United States [18].

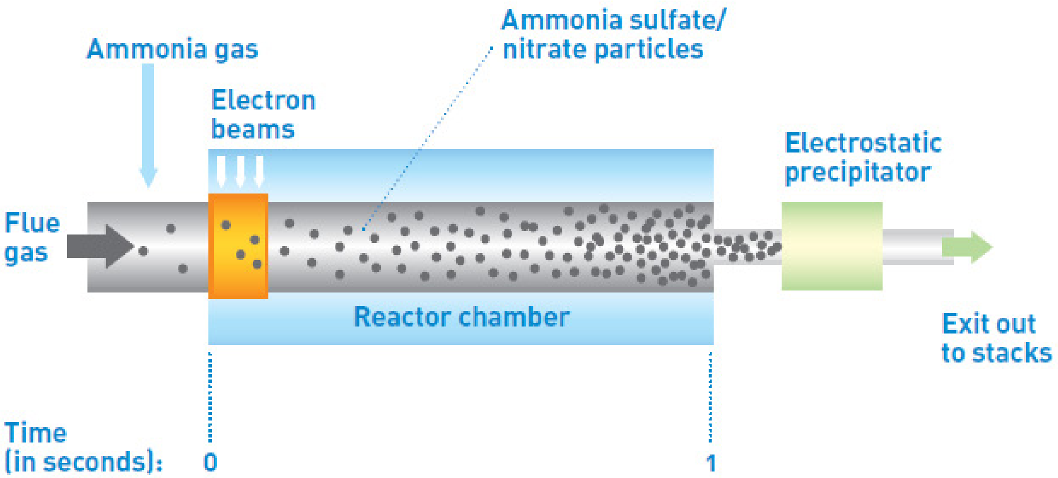
There are several conventional technologies for treating flue gases
are aimed at controlling the emission of sulfur dioxide (SO_2) and nitr
ides (NO_x) into the environment. Some of these technologies are the w
and semi-dry flue gas desulphurization (FGD) and selective catalytic re
(SCR). These conventional gas-cleaning technologies are complex c
processes that result in the generation of wastewater and undesired bypr

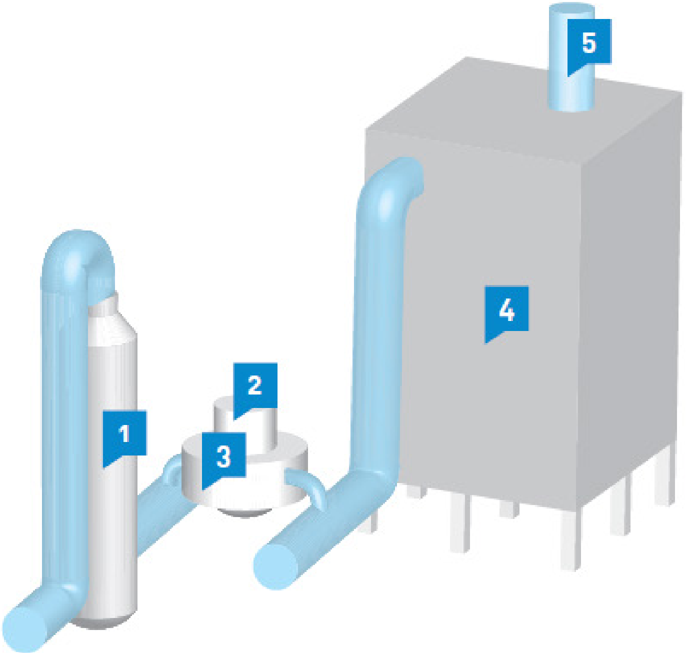
The flue gas treatment using EB accelerators has several advantages over
rrently used conventional metho

1. It simultaneously removes
2. It is a dry process that is lowing capability;
3. The pollutants can be co
4. The process has relatively



The treatment begins with a conditioning tower (1) that cools the flue gas. The cooled gas moves into an accelerator (2), where an electron beam triggers a chemical reaction (3) to convert the sulfur dioxides and nitrogen oxides into ammonium sulfate and ammonium nitrate. The electrostatic precipitator (4) removes the sulfate and nitrate byproducts and collects them to be sold to fertilizer companies. The clean gas goes out the chimney stack (5). *Image source: PAVAC Industries; image: Sandbox Studio*





RADIATION TECHNOLOGY APPLIED IN ENVIRONMENT PROTECTION

Phase	Object	Additives	Process
Gas	Flue gas	SO_2; NO_x	Removal
	VOC	Organic compounds	Degradation, removal
Liquid	Drinking water	Chemical pollutants	Degradation, removal
	Wastewater	Bacteria; viruses; parasites	Hygenizataion
	Industrial wastes	Organic and nonorganic compounds	Degradation, removal
Solid	Sewage sludge	Bacteria; viruses; parasites	Hygenizataion
	Solid materials	Agriculture wastes	Transformation

1. Status of EB FGT Plant

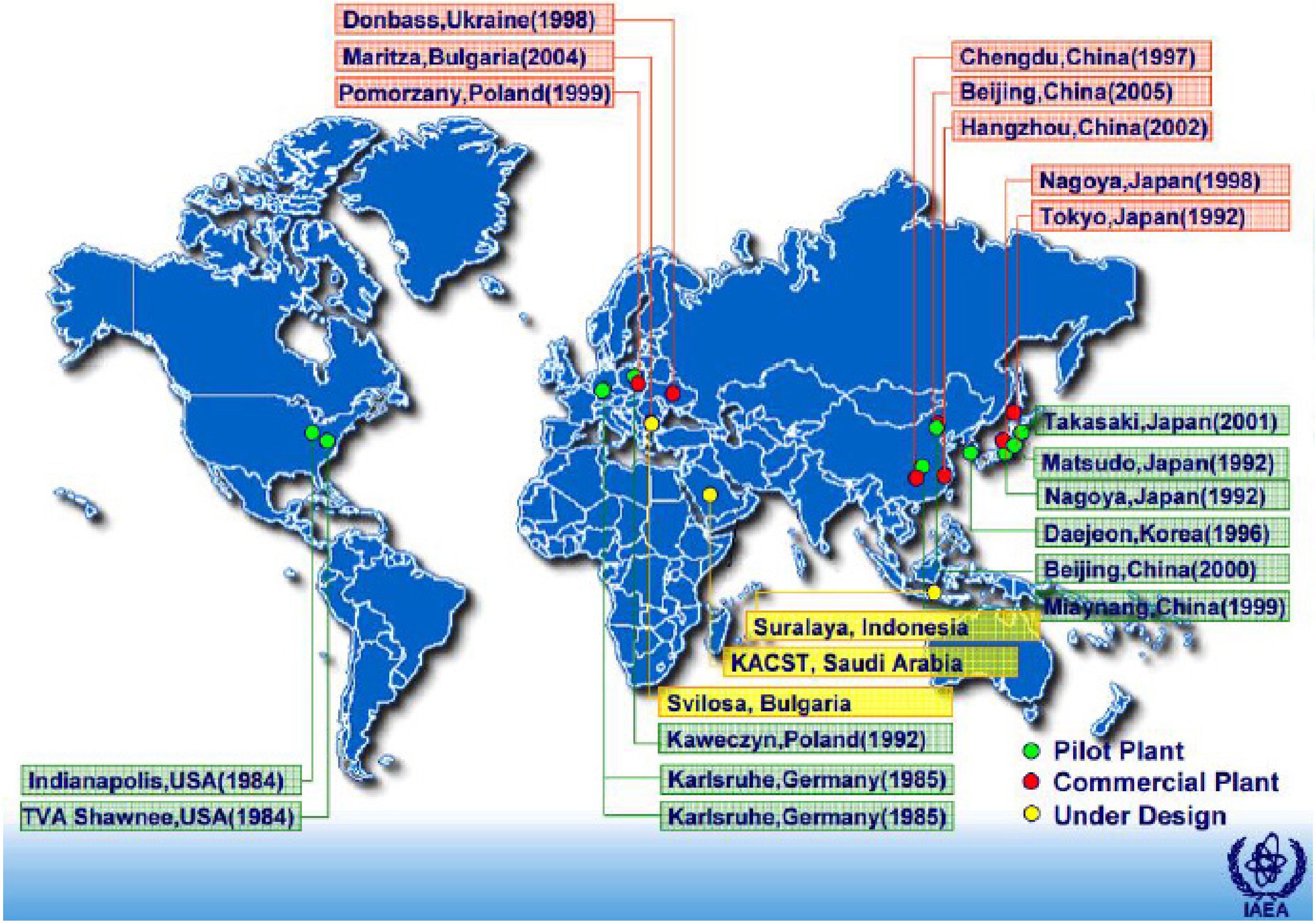
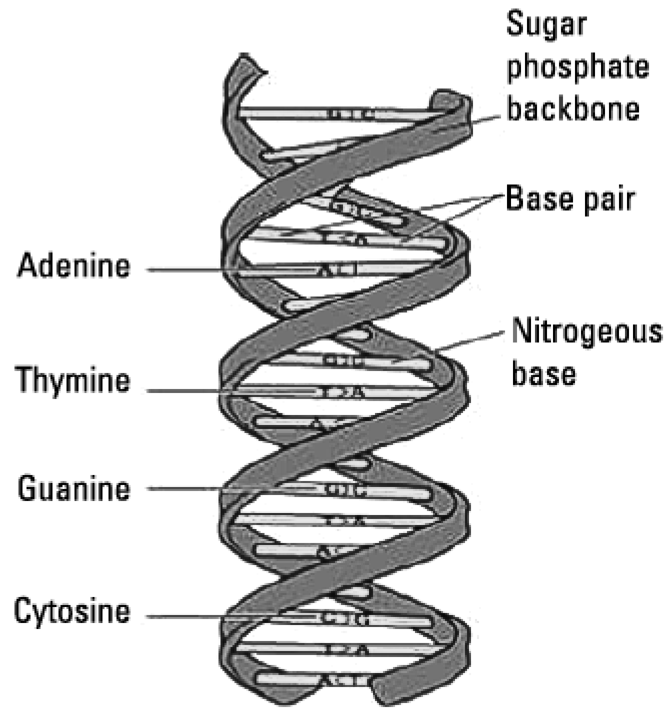


Image courtesy of Zimek Zbigniew, ICNT

Sterilisation

- Electron beams have the ability to double break DNA chains in living organisms such as bacteria and insects. This results in microbial death and hence sterilisation.
  - Applications of this include
  - Medical product sterilisation and antiseptic packaging
  - Live insect elimination in grains and tobacco
  - Disinfecting spices and herbs without fumigation
  - Eliminating fruit flies in fruit and vegtables
  - Fungus treatment in food
  - Salmonella, Listeria, E-coli elimination in foods.



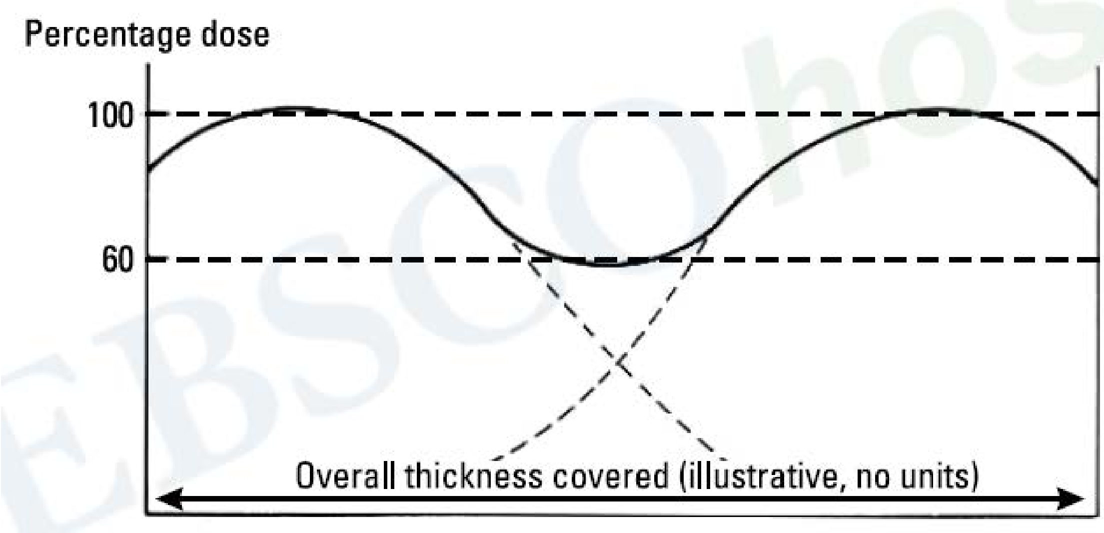
Dose required

Different Food Irradiation Applications and the Doses Used

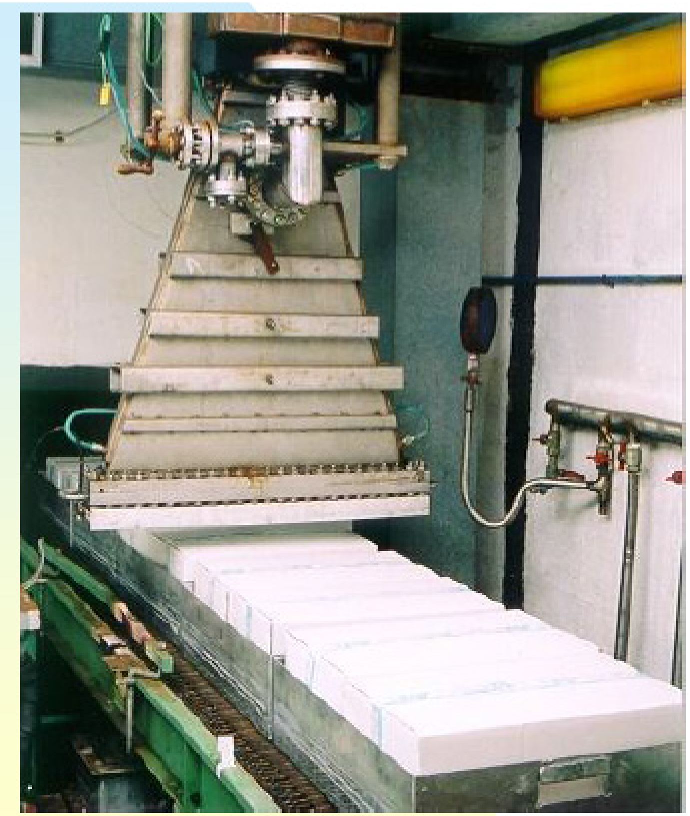
Low-Dose Applications 0.03 to 1 kGy	
Application	**Dose**
Sprout inhibition in bulbs and tubers	0.03–0.15 kGy
Delay in fruit ripening	0.25–0.75 kGy
Insect disinfestations including quarantine treatment and elimination of foodborne parasites	0.07–1.00 kGy
Medium-Dose Applications 1 kGy to 10 kGy	
Application	**Dose**
Reduction of spoilage microbes to prolong shelf life of meat, poultry, and seafood under refrigeration	1.5–3 kGy
Reduction of pathogenic microbes in fresh and frozen meat, poultry, and seafood	3–7 kGy
Reducing the number of microorganisms in spices to improve hygienic quality	3–7 kGy
High-Dose Applications 10 kGy to 70 kGy	
Application	**Dose**
Sterilization of packaged meat, poultry, and their products that are shelf stable without refrigeration	25–70 kGy
Sterilization of hospital diets	25–70 kGy

- The public are often not keen to eat irradiated food (even though it causes no harm)
- As a result some countries have unnecessary regulations which limit usage.

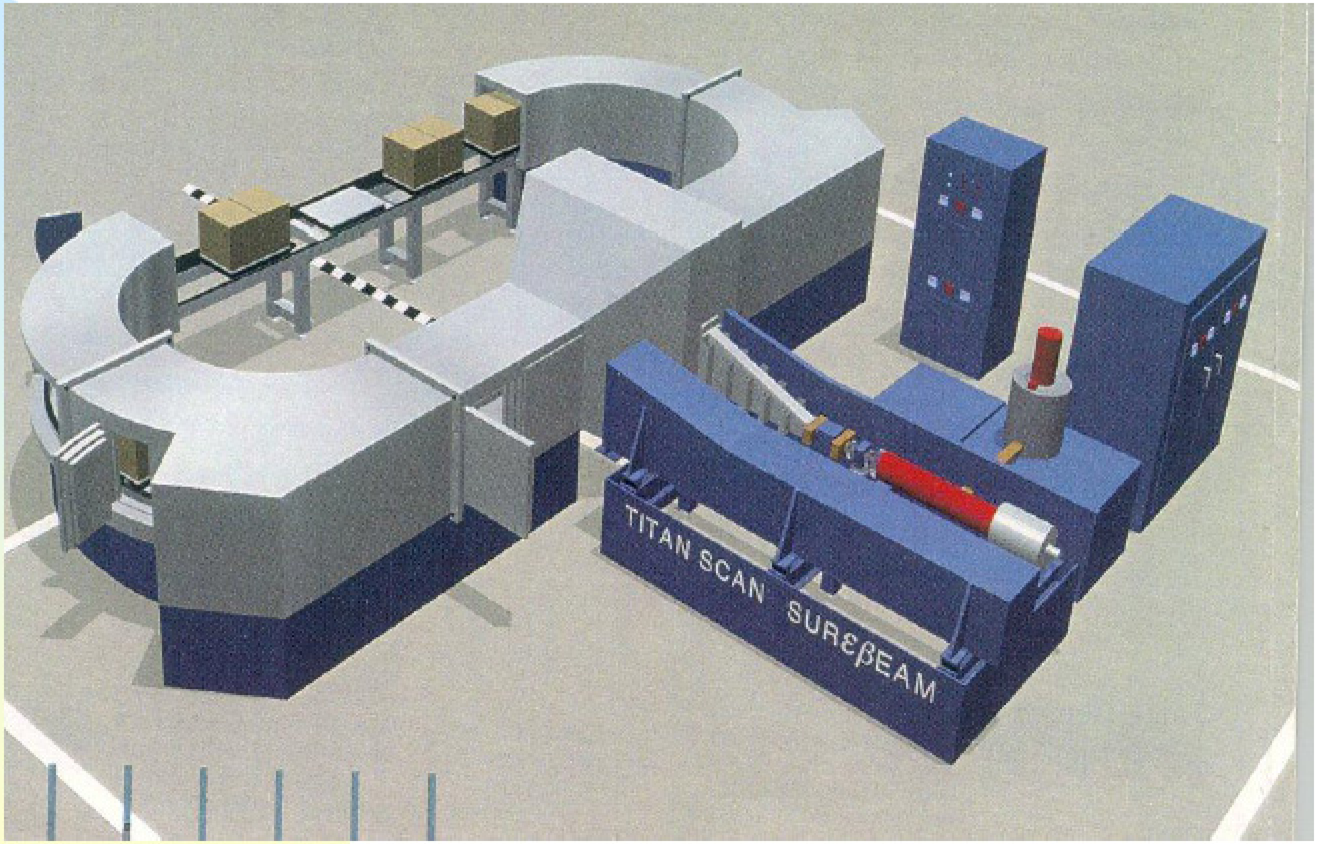
Irradiating from two sides



- Energy required depends on the sample size and density
- As e-beam penetration is low we can use a lower energy by irradiation on both sides
- Normally packaging does two passes of the accelerator and is flipped in between.



10 MeV Sterilisation system



ELECTRON ENERGY	10 MeV	DOSE	10-50 kGy
BEAM POWER	3-5 kW	PRODUCTIVITY	up to 50 000 m³/rok

Image courtesy of Zimek Zbigniew, ICNT

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Requirements

	Low energy	Medium energy	High energy
Energy range	70 keV–300 keV	300 keV–5 MeV	5 MeV–10 MeV
Features	Wide unscanned beams less ≤3 m	Scanned beams ≤3 m	Linacs or SRF
Current applications	• Curing of inks • Crosslinking of polymers • Surface sterilization • Remediation of liquids and gases	• Crosslinking of wire and cable insulation • Crosslink heat-shrinkable plastic tubing • Manufacture of closed-cell foam • Crosslink plastic • Crosslink rubber • Medical sterilization	• Bulk sterilization of medical devices • Crosslinking thicker plastics

Electron accelerators

- DC- Transformer types: Simple but size grows sharply with energy (not linear). Very efficient.
- Single cavity types – Can use very high power RF sources that exist at low frequency (UHF). This means the power transferred to the beam is higher hence fairly efficient. Large transverse size.
- Linacs – Sizes scales linearly with energy. Smaller transverse size as higher RF frequency. Less power is available at higher frequencies so proportionally more of the power goes into RF losses and less to the beam.

Electron accelerators

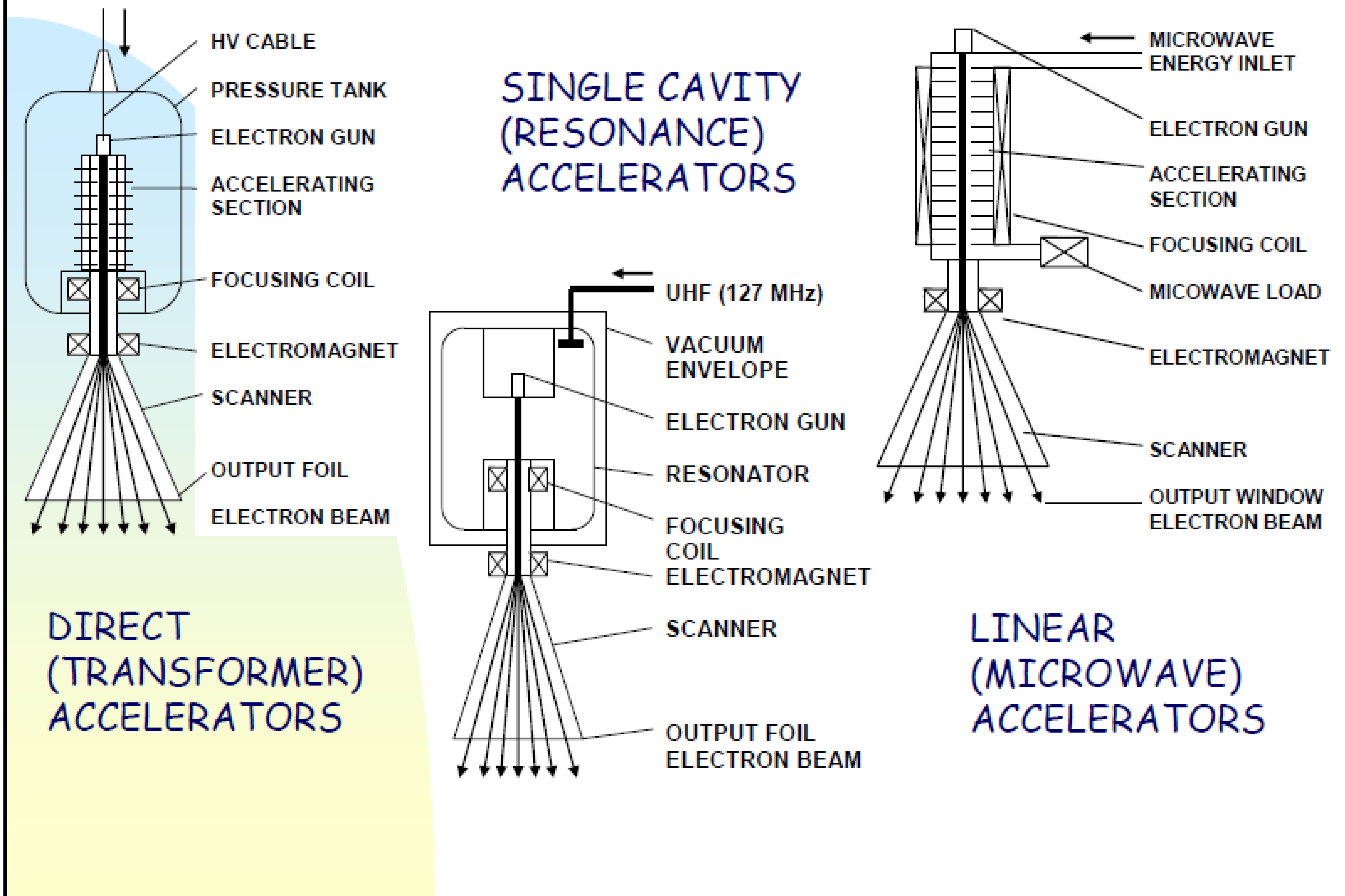
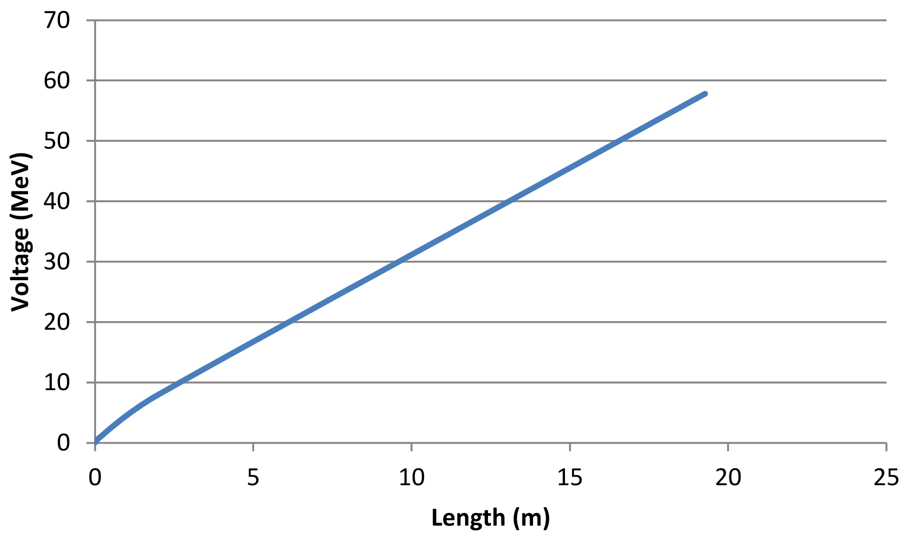


Image courtesy of Zimek Zbigniew, ICNT

Kilpatrick Criterion

- The breakdown (max) voltage for electrostatic accelerators is given by the Kilpatrick criterion. Above this voltage a plasma forms

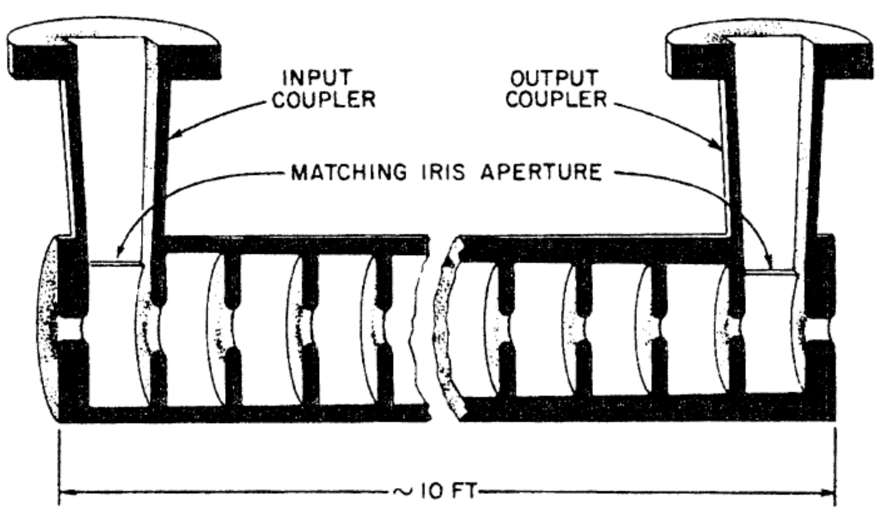
$$VE^2 \exp\left(-\frac{1.7\times10^7}{E}\right) \leq 1.8\times10^{18}$$



DC accelerators are very simple but the achievable gradient is very low for voltages above 10 MeV (around 3 MV/m).
Higher gradients are possible for smaller gaps and hence lower voltages.
In addition it is difficult to generate the high voltage in the first place.

Multicell

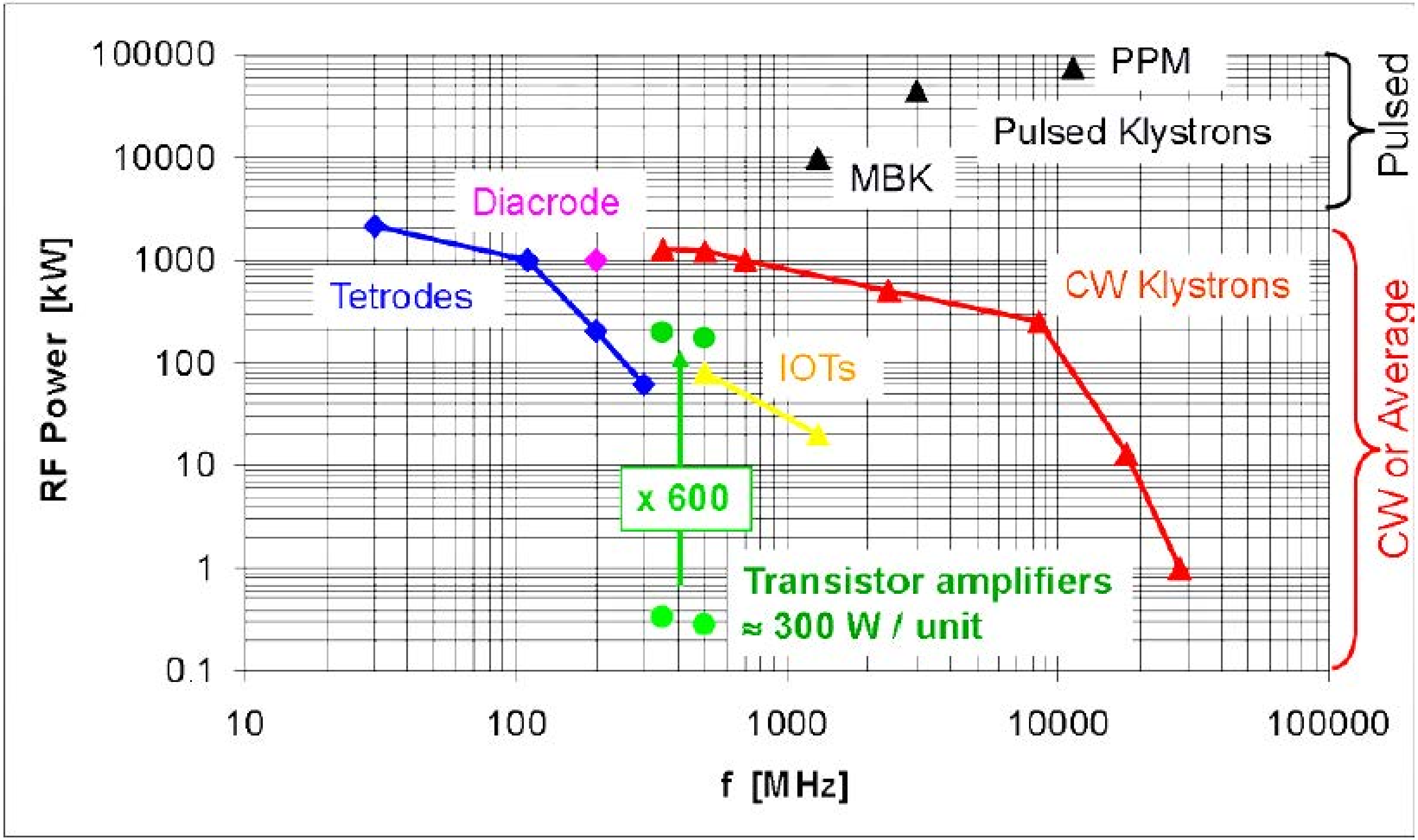
- It takes x4 power to double the voltage in one cavity but only x2 to use two cavities/cells to achieve the same voltage (R_s ~number of cells).
- To make it more efficient we can add either more cavities or more cells. This unfortunately makes it worse for wakefields (see later lectures) and you get less gradient per unit power.
- In order to make our accelerator more compact and cheaper we can add more cells. We have lots of cavities coupled together so that we only need one coupler. For N cells the shunt impedance is given by



$$R_{total} = NR_{single}$$

This however adds complexity in tuning, wakefields and the gradient of all cells is limited by the worst cell.

Power vs. frequency



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Typical Systems

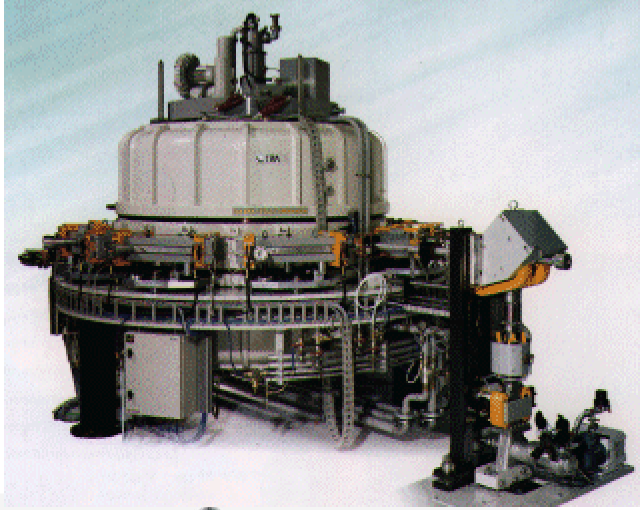
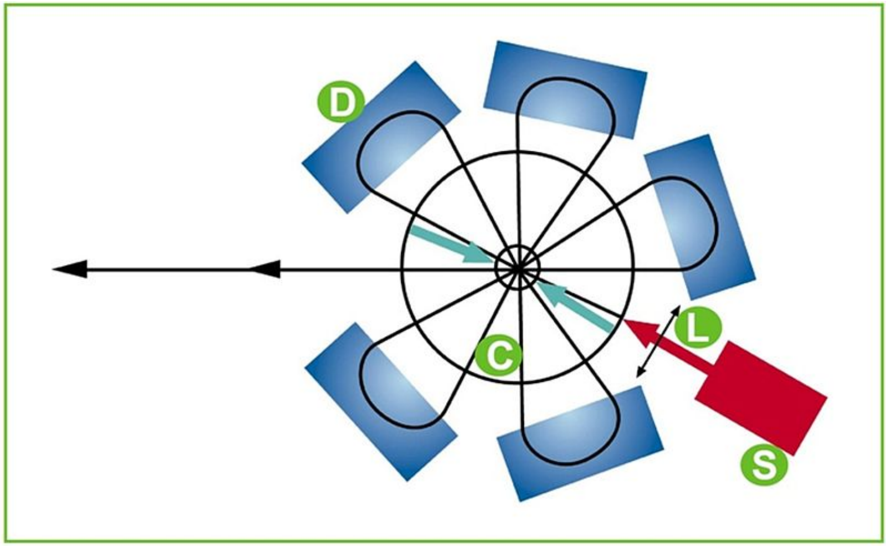
Accelerator type / Parameter	Direct DC	UHF 100 - 200 MHz	Linear microwaves 1.3–9.3 GHz
Av. beam current	<1.5 A	<100 mA	<100 mA
Energy range	0.05 - 5 MeV	0.3 - 10 MeV	2 - 10 MeV
Beam power	~500 kW	700 kW	100 kW
In future	1 MW	1 MW	200 kW
Electrical efficiency	60 - 80 %	20 - 50 %	10 - 20 %

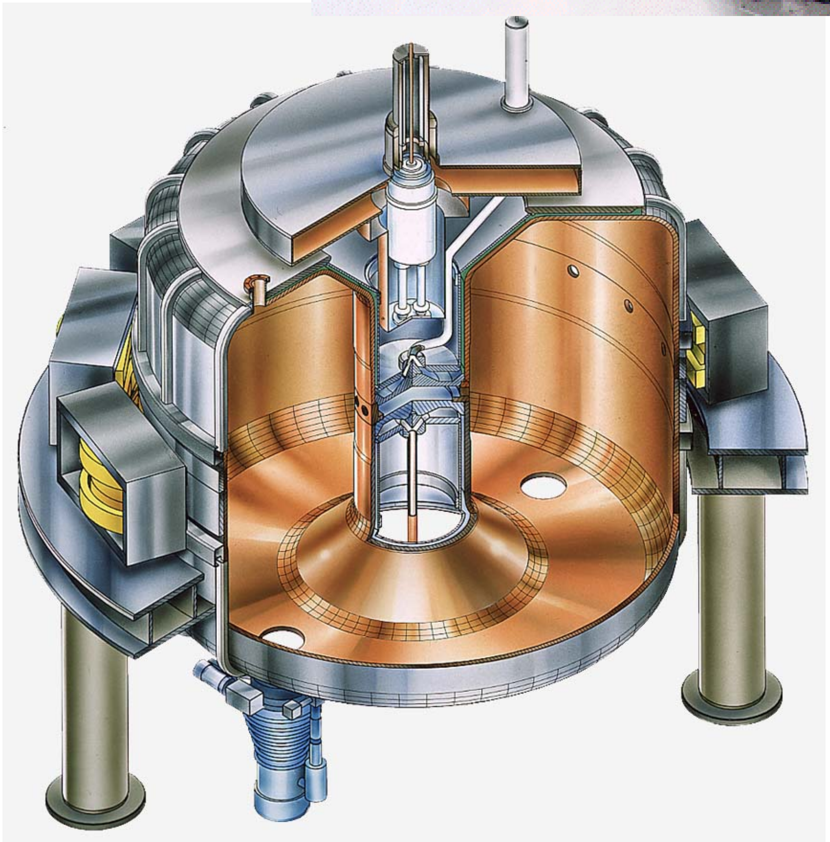
Image courtesy of Zimek Zbigniew, ICNT

IŁU 14 (10 MeV; 100 kW)

Image courtesy of Zimek Zbigniew, ICNT

Rhodotron



- There is also the option of a Rhodotron (IBA) which is less common.
- Can reach 200 kW, 10 MeV at an efficiency of 40-50%.
- Despite what it looks like it is quite simple to maintain (according to IBA)

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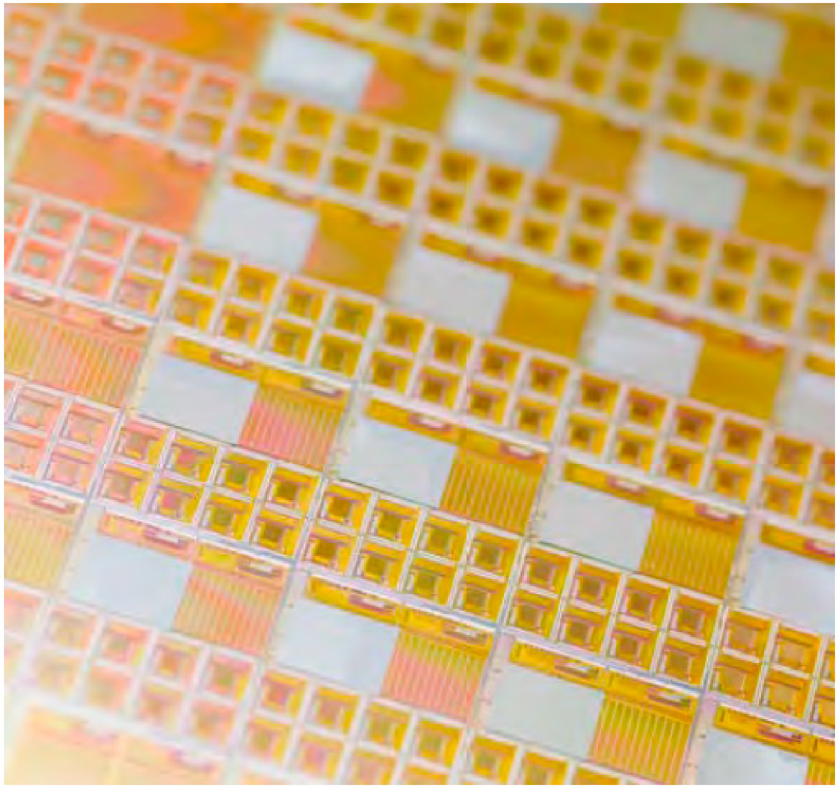
Ion Implanting

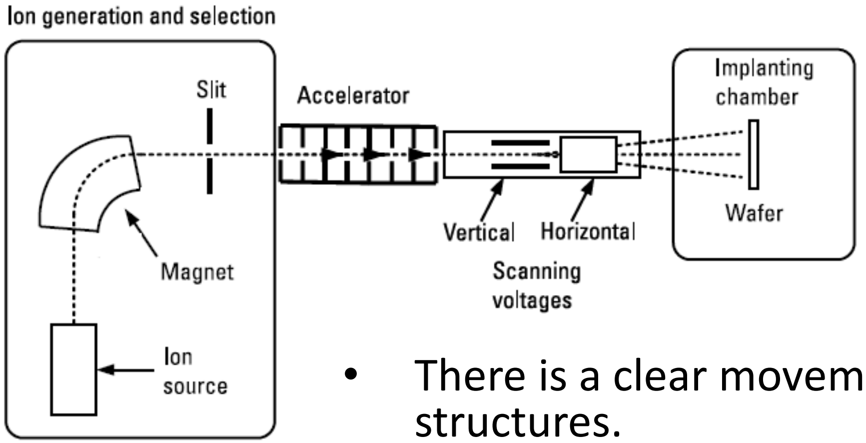
- The semiconductor industry relies on the implanting of impurities in semiconductors (doping).
- This is critical in integrated circuit manufacturing.
- One way of doing this is to fire ions into the material from an accelerator with its penetration dependant on the energy, hence they can be placed accurately in the material.
- Ion implanting is the only method to accurately control the ion position from the equipment settings.



About 10,000 accelerators are in use worldwide to "dope" the silicon or germanium base to create electronic circuitry for computer chips. *Photo: Reidar Hahn, Fermilab*

High-Current Ion Implanters		Medium-Current Ion Implanters		High-Energy Ion Implanters	
Ion Current	Energy	Ion Current	Energy	Ion Current	Energy
Up to 30 mA	1 keV to 200 keV	1 micro A to 5 mA	2 keV to 900 keV	up to 1 mA	up to 5 MeV

Modern developments



- There is a clear movement to plasma implantation for new device structures.
- However research in areas of quantum computing requiring the precision to place single ions with nm spatial positioning is a potential challenge.
- Also research in opto-electronic devices still requires quite complex recipes for ion implantation.
- Ion implantation is still one of the most controllable and reliable techniques for incorporating a precise amount of one material in another. The role of ion implantation in producing buried nano structures for a whole range of optical, magnetic and electronic applications will continue long into the future.
- The ability to place single ions at nm depths and with similar spatial resolution are key to producing nanostructures on a large scale.