Industrial Applications via Novel Compact Electron Beam Accelerator

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Summary

1. Fermilab is a basic discovery science lab answering fundamental questions
   - The primary discovery tool is the particle accelerator
   - Fermilab is using over 5 decades of experience with HEP machines to make an industrial compact accelerator
2. Fermilab compact accelerator used to treat thick films at high rates
3. E-beam well established tool in industry with current applications
4. Compact accelerator will enable new applications: (Thick Films – Pavement, Environmental Remediation, Medical Sterilization, Phytosanitation)
   - Advantages of accelerator – small footprint, high penetration depth, treat high flow rates, high energy efficiency (compared to electrostatic e-beam)
5. Concurrently developing applications in A2D2
6. Outreach efforts to help tell about technologies (Water, Med Ster, Acc Stew)

1. Fermilab at a glance

America's Particle Physics and Accelerator Laboratory

As the United States' premier particle physics laboratory, we do science that matters.

FERMILAB PROCUREMENT FY18

$183 M+
U.S. SPENDING

$63 M+
ILLINOIS SPENDING

$58 M+
SMALL BUSINESS CONTRACTS

USER FACILITIES

Fermilab Particle Accelerator Complex

U.S. Hub for the CMS Experiment at the Large Hadron Collider at CERN

FOR MORE INFORMATION
Email: fermilab@fnal.gov
www.fnal.gov

$437 M
BUDGET IN FY18

MAJOR PARTNERSHIPS

Deep Underground Neutrino Experiment
World's flagship neutrino experiment with more than 1,000 scientists from over 30 countries

PIP-II particle accelerator
215-meter-long particle accelerator to be constructed at Fermilab with major international contributions

LCLS-II X-ray Laser
Design and construction of 19 superconducting cryomodules needed for the LCLS-II X-ray laser at DOE's SLAC laboratory

Quantum Science
Apply expertise and knowledge in quantum systems in collaboration with industry and other research institutions

4,800+
Employees, scientists from across the U.S. and over 50 countries use Fermilab's accelerators, detectors and computing facilities each year

31,000+
Students in K–12 programs

2,300+
PhDs based on research at the lab

230+
Teachers attending workshops

FLAGSHIP LBNF / DUNE PROJECT

$1 B+ ECONOMIC OUTPUT

Estimates based on first decade of planning, construction and operations

$500 M+
LOCAL **EARNINGS**

$20 M+
ILLINOIS TAX **REVENUE**

1. DUNE Science Goals

Origin of matter

Discover what happened after the big bang: Are neutrinos the reason the universe is made of matter?

Black hole formation

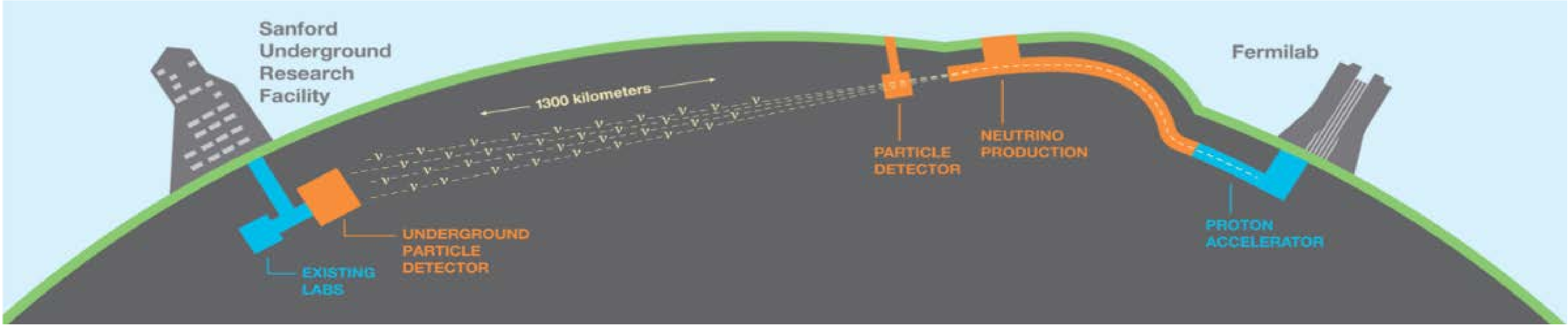
Use neutrinos to look into the cosmos and watch the formation of neutron stars and black holes in real time

Unification of forces

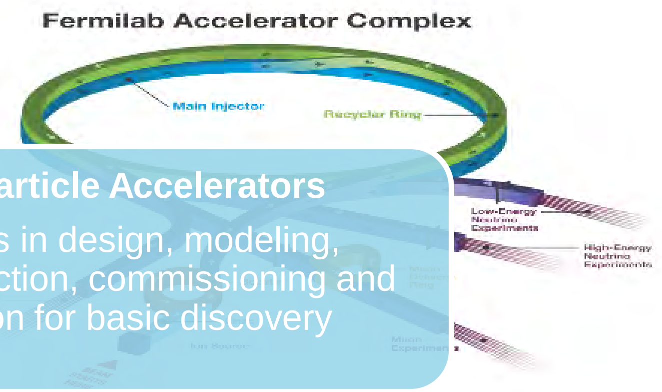
Move closer to realizing Einstein’s dream of a unified theory of matter and energy

1. Building for Discovery

- Lab strategic plan is aligned with the P5 Plan
- Fermilab's primary 10-year goal: a world-leading neutrino science program
  - Anchored by the Long-Baseline Neutrino Facility (**LBNF**) and Deep Underground Neutrino Experiment (**DUNE**)
  - Powered by megawatt beams from an upgraded and modernized accelerator complex made possible by the Proton Improvement Plan II (**PIP-II**) First international mega-science project based at a DOE national laboratory

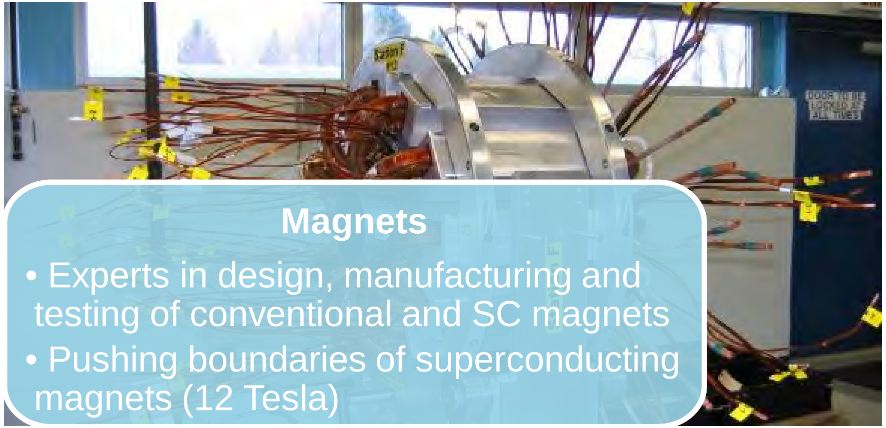


1. Fermilab Science → Fermilab Technology



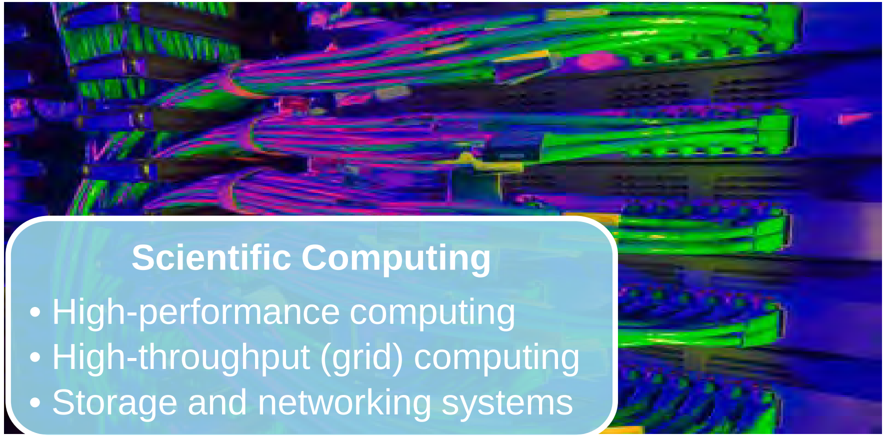
Particle Accelerators

- Experts in design, modeling, construction, commissioning and operation for basic discovery science



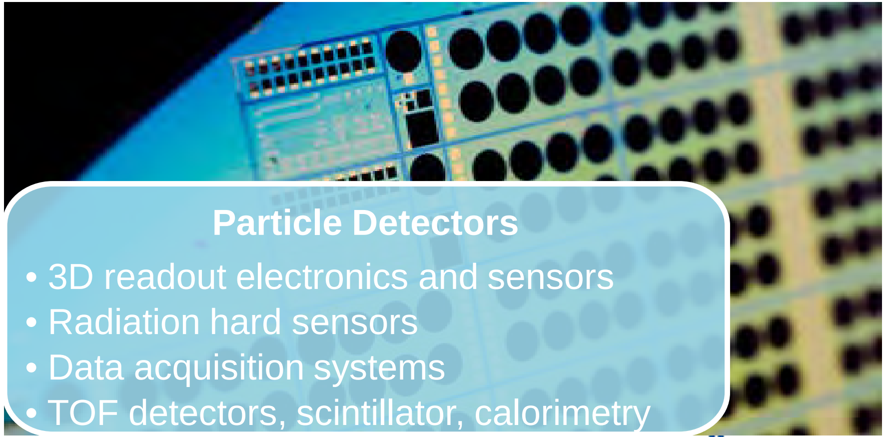
Magnets

- Experts in design, manufacturing and testing of conventional and SC magnets
- Pushing boundaries of superconducting magnets (12 Tesla)



Scientific Computing

- High-performance computing
- High-throughput (grid) computing
- Storage and networking systems



Particle Detectors

- 3D readout electronics and sensors
- Radiation hard sensors
- Data acquisition systems
- TOF detectors, scintillator, calorimetry

1. Fermi National Accelerator Lab

- Vision is to solve the mysteries of matter, energy, space and time for the benefit of all
- In completing basic discovery science mission existing technologies are improved and new ones are created

Illinois Accelerator Research Center

- Further develops Fermilab technologies so they can be utilized externally
- Access to Fermi's infrastructure
- Accelerators, magnets, detectors and computing

2. Curing of Thick Coatings

- **Fermilab is developing a novel E-beam accelerator**

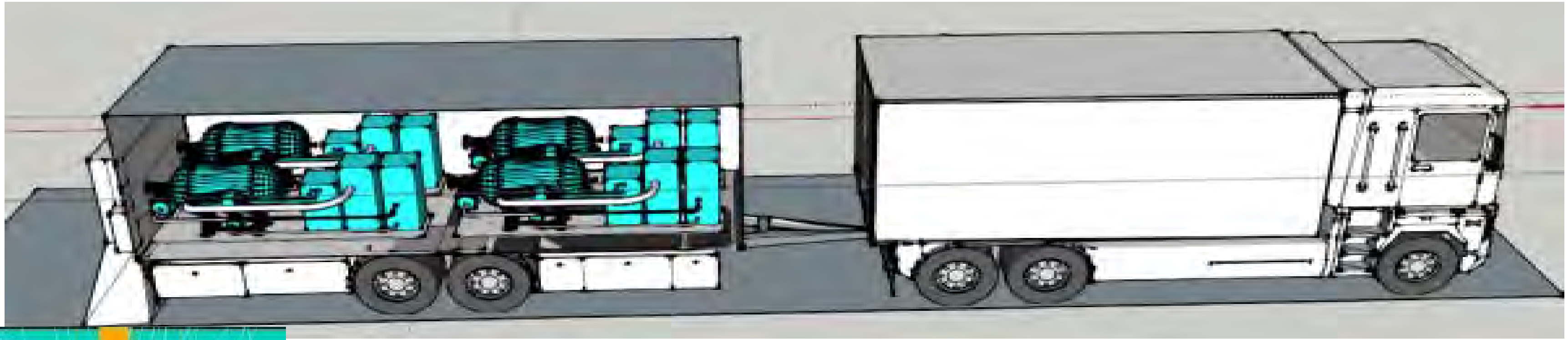
  Compact: Portable and more easily integrate into existing infrastructure

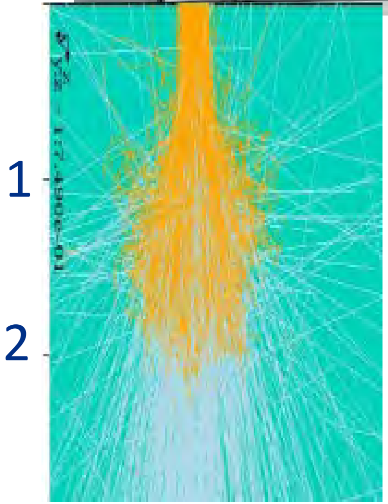
  10 MeV: Can process thick composites with cross-sections up to 5 cm

  250kW: 90,000 kg/hr at 10 kGy

- Current electron beams used for curing can deliver curing energy up to 200 microns beneath the surface of a coating layer.

2. Compact Accelerator for Pavement



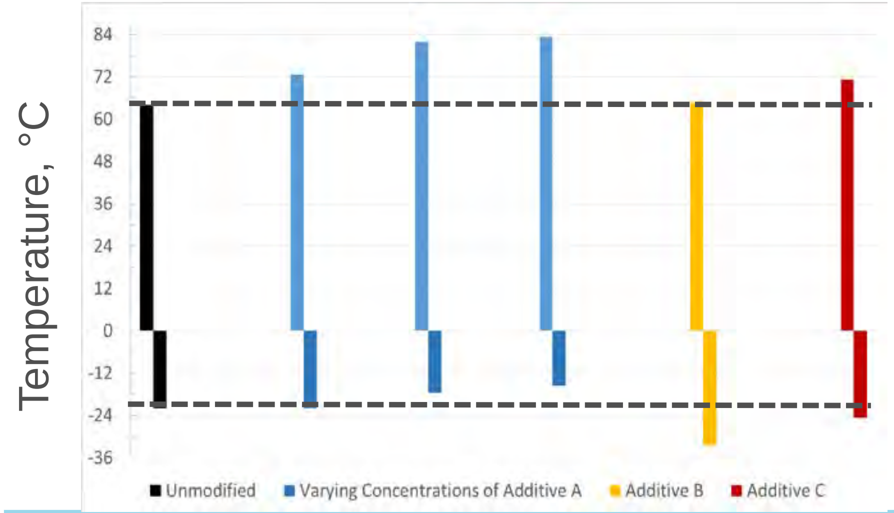


- High power and good penetration depth allow for rapid deployment of new pavement
- Enables use of new types of pavement materials that are more resilient to wear than asphalt
- Can be used for applications like military runways, specialty coatings and normal roadways
- Penetration depth allows for cold repairs

U.S. Patent #9,186,645 & 9,340,931

2. E-beam Effects on Bitumen Systems

- E-beam irradiation of unmodified bitumen had little effect, likely because already highly crosslinked by sulfur.
- Effect of crosslinking via E-beam for various additives shown.
- Potential to custom blend formulation to meet desired operation parameters
- Largely drop in technology with added step of E-beam irradiation

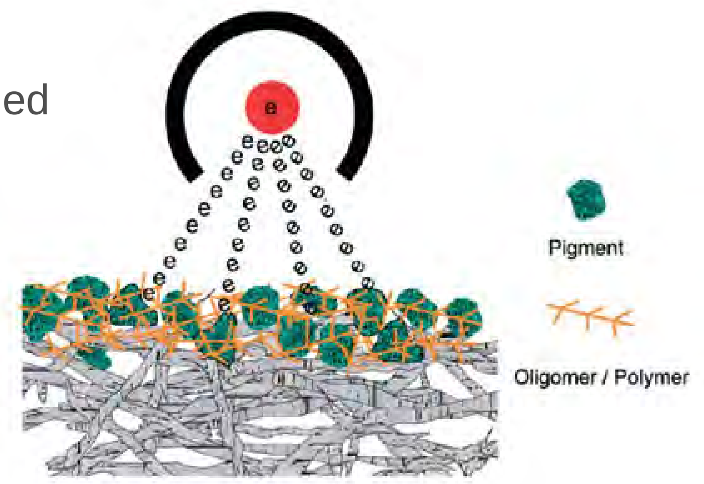


Minimum Temp, °C	Average 7-day Max Temp, °C 52	58	64	70	76	82
-16	52-16	58-16	64-16	70-16	76-16	82-16
-22	52-22	58-22	64-22	70-22	76-22	82-22
-28	52-28	58-28	64-28	70-28	76-28	82-28
-34	52-34	58-34	64-34	70-34	76-34	82-34
-40	52-40	58-40	64-40	70-40	76-40	82-40

Crude Oil
High Quality Crude Oil
Modifier & Crude Oil

3. Curing Technologies

- Thermal Curing
  - An oxidation process that relies on evaporating a water-based or solvent-based dilutant, leaving the pigment or other functional additives bound in a resin matrix
  - Inefficient (lose most heat to substrate)
  - Cannot be used with heat-sensitive substrates
- Photocuring (UV irradiation)
  - Highly selective reaction, photoinitiator chemical needed
  - Cannot be used with highly pigmented coatings
- **Radiation Curing (Electron Beam)**
  - Room temperature conditions
  - Can be used on opaque materials
  - Control rate of reaction through dose rate
  - No solvent required

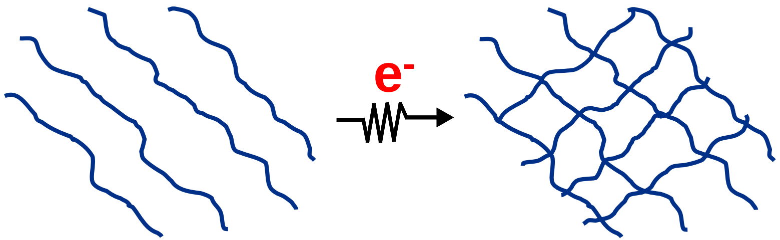


3. What is an electron beam?

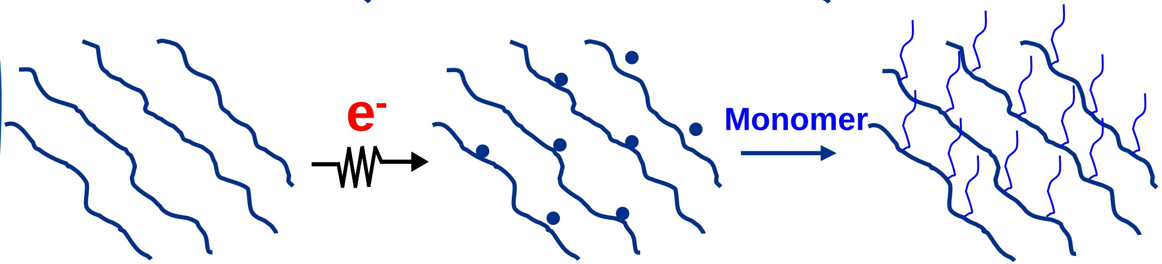
- A controlled stream of electrons that are propelled at a high rate of speed.
  - The most common low intensity e-beam is the cathode ray tube (CRT) used in televisions and computer monitors.
  - Electrostatic – 300 keV
- E-beam based technologies offer a great alternative to traditional industrial processes which are typically energy-consuming and can involve chemicals that damage the raw materials and pollute the environment.
- The main processes initiated by e-beam
  - polymer modification by crosslinking or scission
  - reduction of pathogens
  - decomposition of industrial effluents
  - synthesis of a new substances

3. The Three E-beam Effects based on Free Radicals

Link it – let it bond to itself
Crosslinking of materials



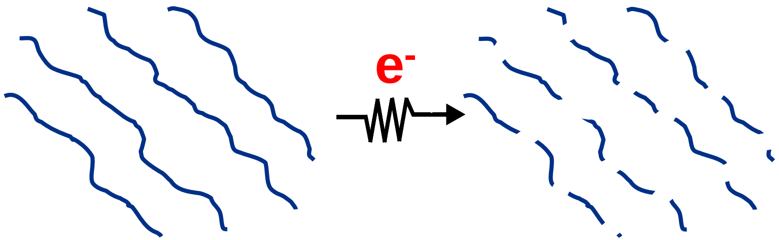
Paste it – let it bond to something else
Radiation grafting



Free radicals

Grafted polymer

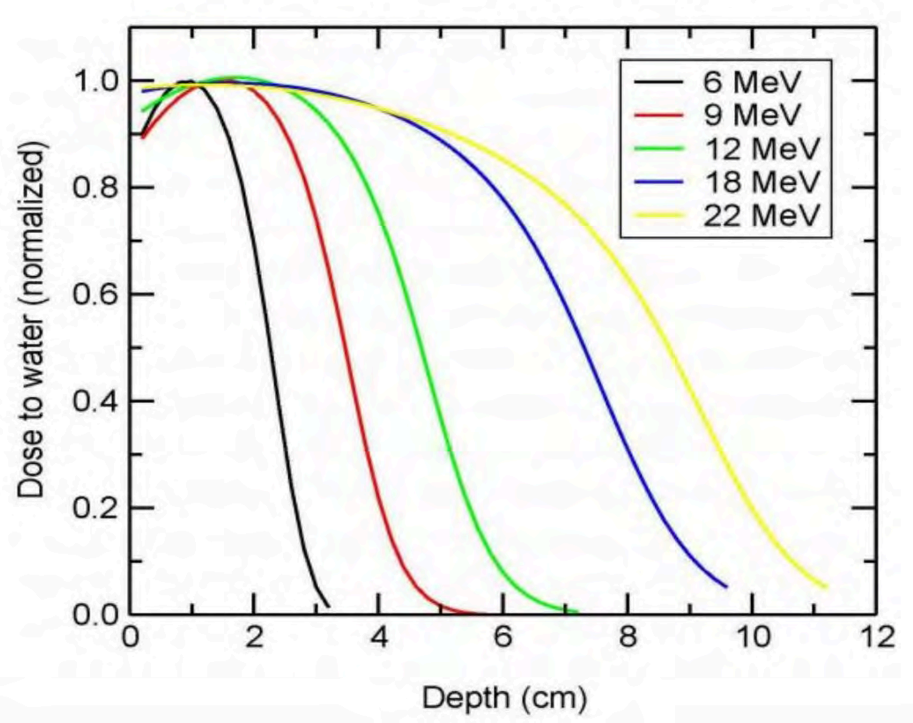
Cut it – leave it broken
Chain scission or DNA damage in med. sterilization



Broken Chain

3. E-beam Processing

- Energy = penetration in target material
- Up to 10 MeV: No radioactivity induced
- Electron beam properties
  - Beam directed toward products
  - Finite product penetration
  - Controlled treatment zones
  - High dose delivery giving short treatment
  - Wide range of energy and power ratings
  - Equipment can be switched on and off



Power = treatment speed

P (kW) = E (MeV) x I (mA)

3. An Established Tool for Industrial Applications

- Industrial electron beams are an exceptional source of energy that are **capable of initiating chemical reactions**

Eliminate high temperature & high pressure

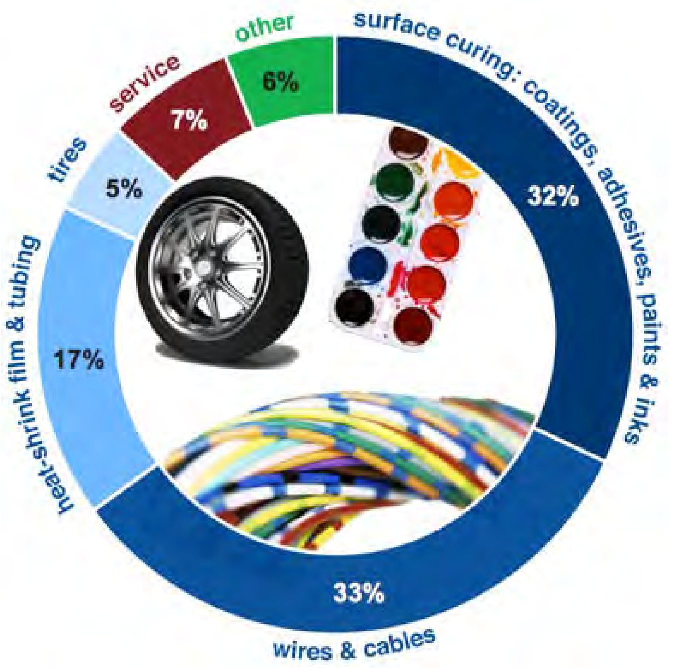
No need for chemical initiators and catalysts

Improve physical & chemical properties of materials

Savings compared to conventional technology

- ➢ Tire industry **16% of manufacturing cost per tire**
- ➢ Cable insulation **18% of avg. cost per km of product**
- ➢ Curing **25-65% of manufacturing cost**

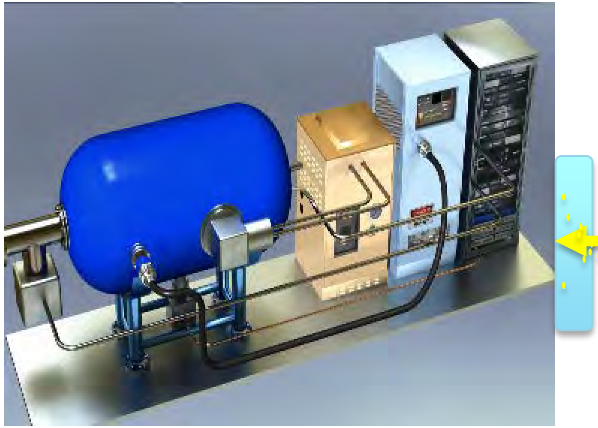
There are more than 30,000 accelerators in the world covering a wide range of applications

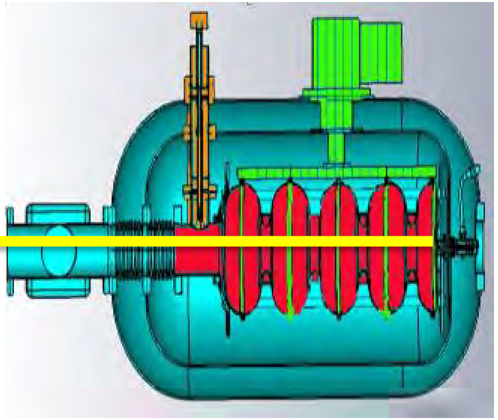


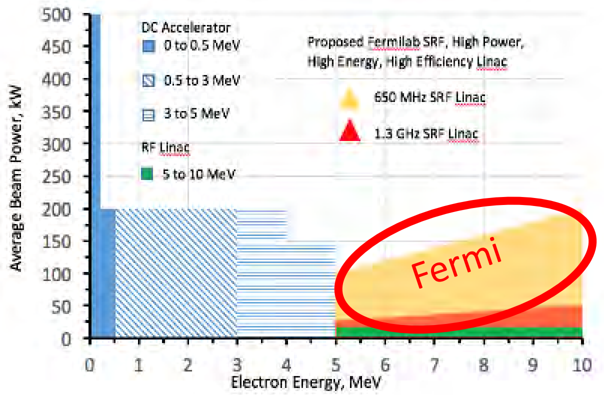
Current End-use Market Distribution of Electron Beam Industrial Applications

87% of these e-beam processes involve crosslinking, represented by the applications in blue segments

4. Novel E-beam Accelerator

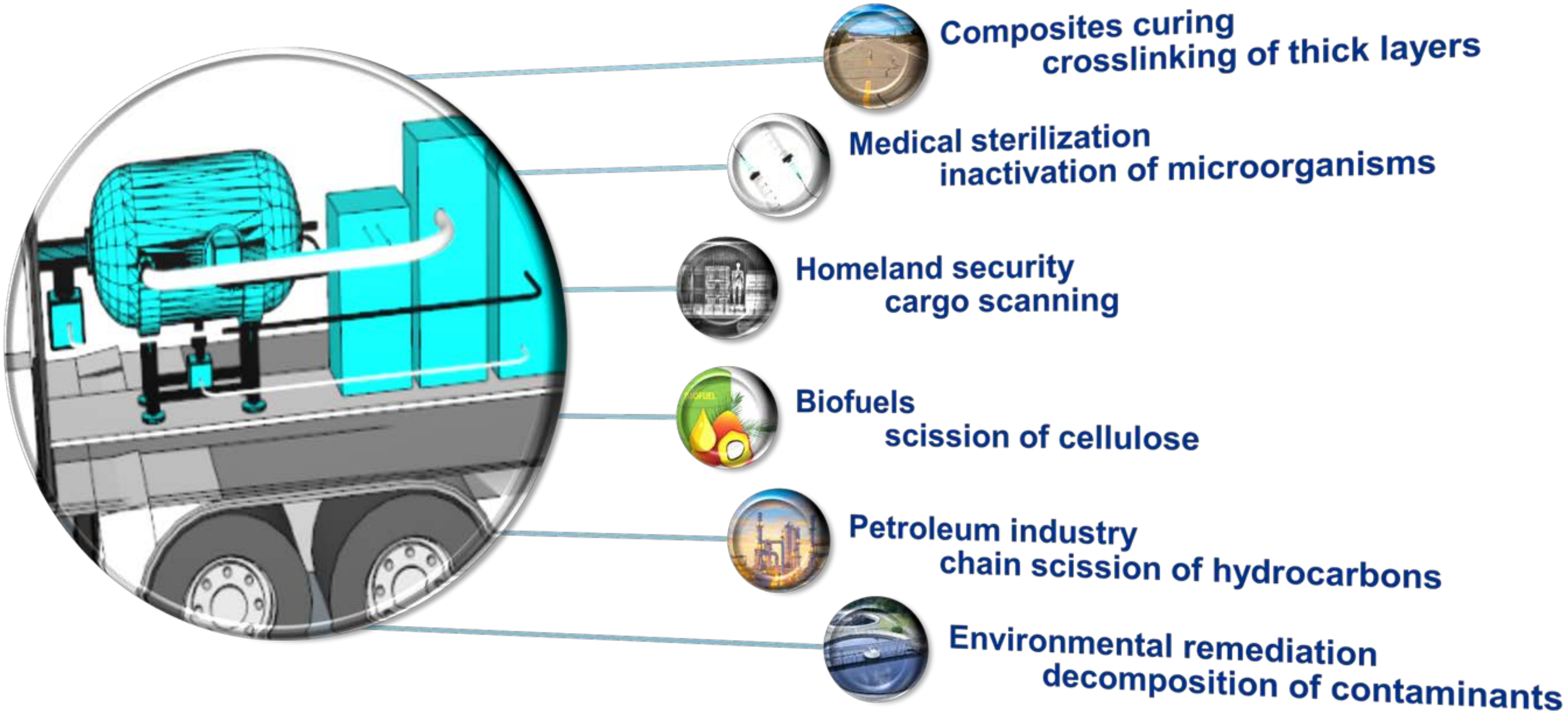






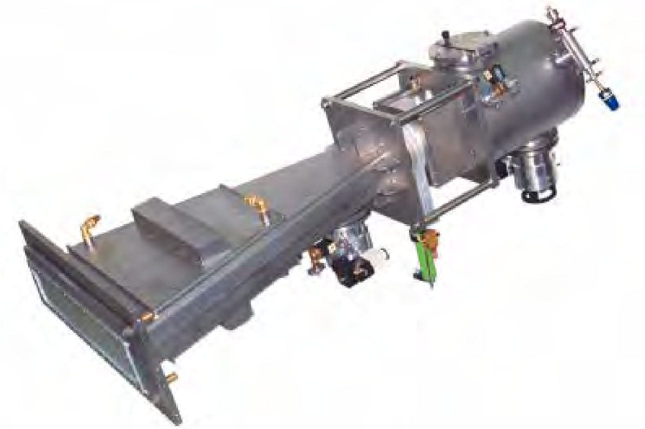
Property	Advantage	Effect	Enabling Technology
High Power	High Throughput	200,000 gal/day (Industry)	Superconducting
Compact	Portable, Integration into infrastructure	5ft by 7 ft by 13 ft (3 Story Building)	Conduction Cooling
Energy Efficient	Reduced OpEx	30% less OpEx (50% less power)	RF Power Supply Superconducting

4. Emerging E-beam Applications



4. E-beam Curable Coatings

- Electron beams are used to polymerize a mixture of reactive monomers, colorants, surfactants and other additives
- The result is a high-quality coating, made without solvents or adhesives
  - Environmentally-friendly
- Products include floor coverings, tape, barrier layers for packaging, fiber optic coatings and sealants

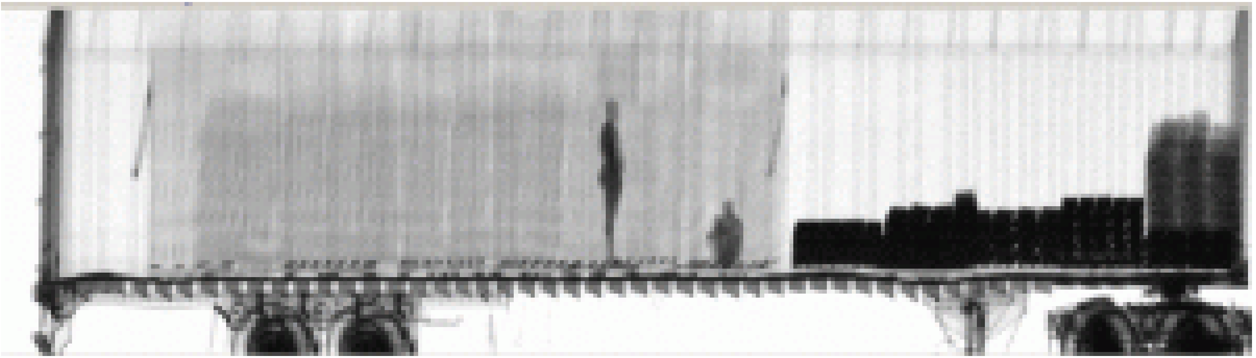


4. Medical Sterilization

- Harmful microorganisms are completely inactivated with no effect on the medical supplies.
- Sterilization options
  - Steam – incompatible with most polymers
  - Ethylene oxide gas – explosive, toxic and harmful to the environment
  - ^{60}Co irradiators – require radioactive sources to operate, associated with secure transportation and disposal concerns as well as annual regulatory requalification.
- E-beam
  - Directed radiation → Efficient use
  - Lowest cost of sterilization for large capacities
  - Can be turned OFF → safer
  - More complex dose mapping

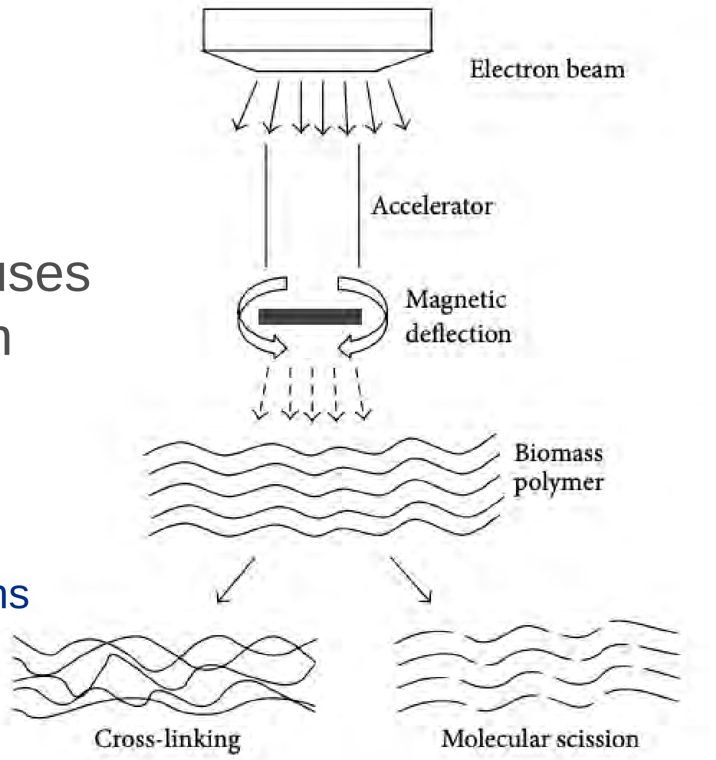
4. National Security

- High-energy X-rays generated by particle accelerators vs. Co-60 scanners
- Detect threats, such as special nuclear material (SNM) or weapons in ship-borne cargo containers
- Electron beam accelerators produce higher energy X-rays, which can penetrate deeper than existing systems and provide more information about the nature of the cargo.
- Replacement of Co-60 due to its radioactive nature.



4. Utilization of Biofuels

- Production of bio-fuels, in particular cellulosic ethanol, is one of the most critical and challenging problems in the fight for energy security and for reducing carbon emissions.
- Exposure of cellulose to ionizing radiation causes significant breakdown of the polysaccharide in trees, plant material, agricultural wastes and algae.
    - ➢ Increased rate of hydrolysis
    - ➢ Hydrogen bonds are broken between cellulose chains
    - ➢ Reduction in crystallinity
    - ➢ Mechanical strength reduction
    - ➢ Increase in the solubility and reactivity of cellulose



4. Petroleum Industry – E-beam scission of hydrocarbons

- E-beams can improve the quality of heavy oil by a relatively low temperature process of converting it to lighter oil with lower sulfur and heavy metal ion contaminants
  - The presence of oxygen is known to enhance the scission of high molecular weight hydrocarbons during exposure to low dose rates of high energy electron beams.

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4. Environmental Remediation of Soil

- Electron accelerators are effective at destroying toxic organic contaminates in soil (PCBs, Explosives, TCE)
- Typically large volumes of material are removed from contaminated areas creating concern of secondary contamination
- Large transportation costs associated with removal of material and replacement of removed material.

Compact accelerator enables new in-situ environmental remediation or decontamination processes

4. E-beam Water Treatment

$$H_2O \xrightarrow{\text{Electron Beam}} OH^* + e^-_{aq} + H^* + H_2O_2 + H_3O^+ + H_2$$

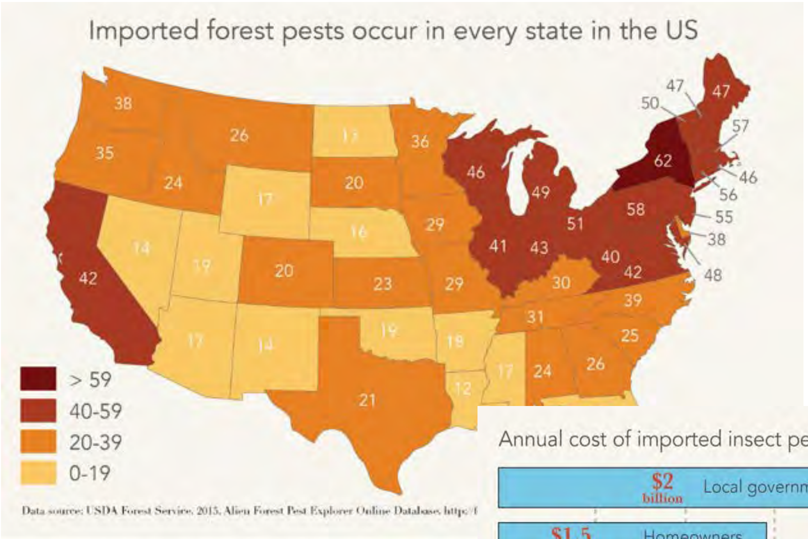
- Increases dewaterability
- Removal of toxic chemicals not removed in conventional domestic water treatment: pharmaceuticals, agricultural run off, fuel additives (MTBE), PCBs, PFAS/PFOA - perfluorinated compounds
- Reduction in pathogens
- No toxic residuals (no secondary waste generation)

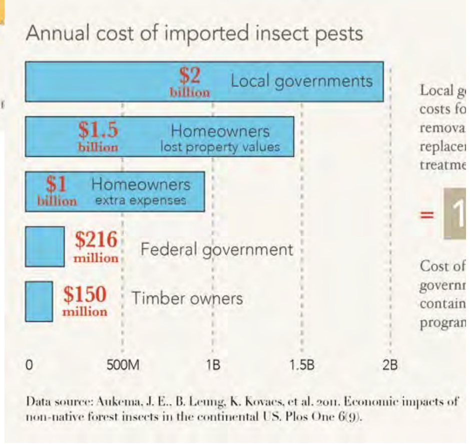
Picture of conventional e-beam

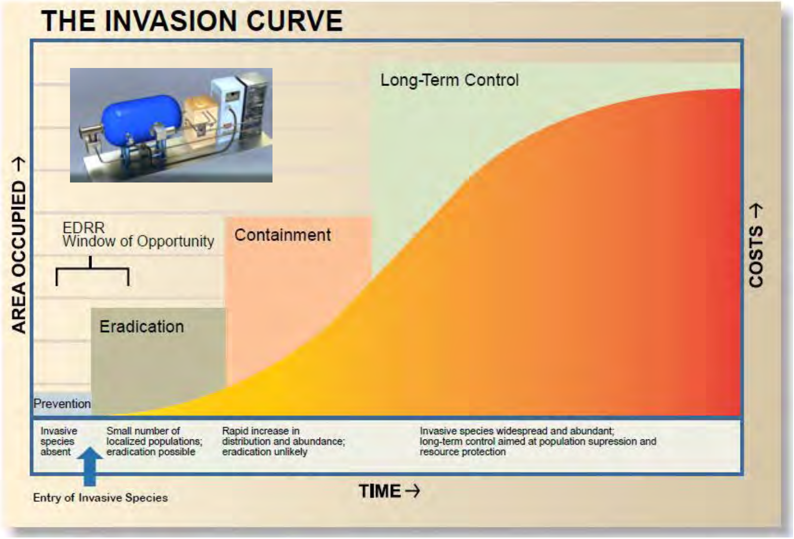
Conventional E-beam technology shown to remove many contaminants in water but:

- **Low throughput**
- **Energy intensive**
- **Large, nonportable footprint**

4.Forest Invasive Species – Early Detection & Rapid Response







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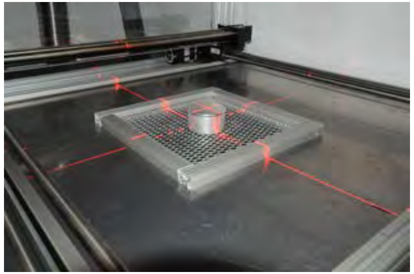
5. A2D2 (used for current projects)

- IARC's accelerator
  - The Accelerator Applications Development and Demonstration (A2D2) is the tool we use verify electron beam proof-of-concept for individual applications
  - A 9 MeV electron accelerator with adjustable dose rates and sample positions available for use by industry, universities, and other government labs.
- Current projects
  - Hardening pavement – crosslinking of pavement compounds
  - Environmental remediation – improving wastewater treatment

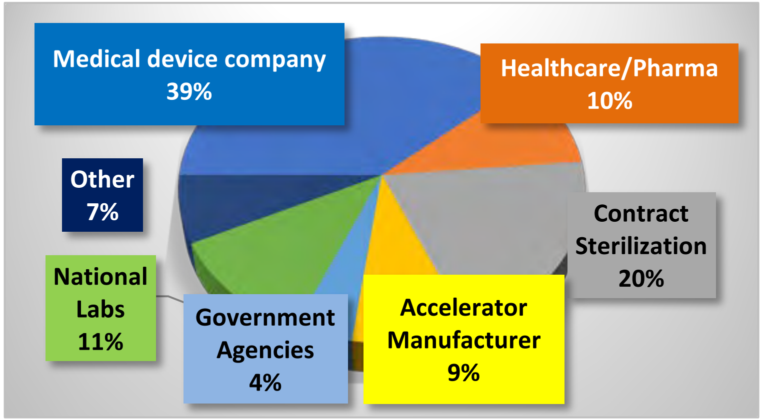


6. Outreach Efforts

- Water Workshop
  - Promote use of e-beam technology for wastewater and biosolids treatment
  - Inform water treatment professionals about e-beam technology and opportunities
  - Provide feedback to NSF to open future funding opportunities
- Medical Sterilization Workshop
  - Focus on the current state of medical device sterilization
  - Educate participants on the fundamental principles
  - Address what information is needed to ease regulatory approval
- Accelerator Stewardship Workshop
  - Learn how to access accelerator and beam facilities at Fermilab for developing and testing new accelerator technologies
  - Interact with experts, tour facilities, and explore new applications of particle accelerators.

6. Midwest Medical Device Sterilization Workshop September 16&17, 2020, Fermilab

- Ethylene oxide concerns in Illinois, Michigan, Georgia
- NNSA desires to reduce dependence on Co-60 & enable alternative technologies
- Baxter / Fermi interaction.



2019 Workshop

- Theme 1: You are Here (Current Paradigms and Drivers in Medical Device Sterilization)
- Theme 2: The Right Tool for the Right Job (Considerations for choosing your Sterilization Method)
- Theme 3: Flipping the Switch (Moving from planning to implementation)
- Theme 4: Accelerating the Path Forward (Prioritizing needs, opportunities, and points for collaboration)

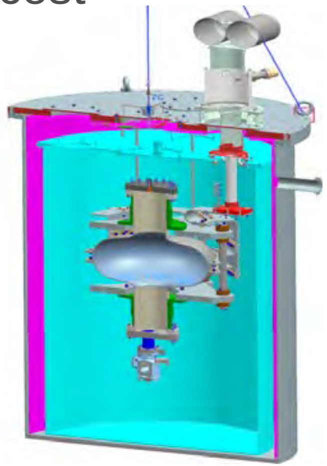
6. Accelerator Stewardship Workshop

Accelerator technology developed in Department of Energy complex for discovery science

For widespread industrial applications need:

- Reduced capital and operating cost
- Improved power efficiency
- Ease of operation
- High Uptime – Robust Tech

- Education – lack of familiarity



Annual funding opportunity announcement to develop 0.5 to 10 MeV e-beam accelerators with power > 1 MW

For:

– Water/sludge decontamination

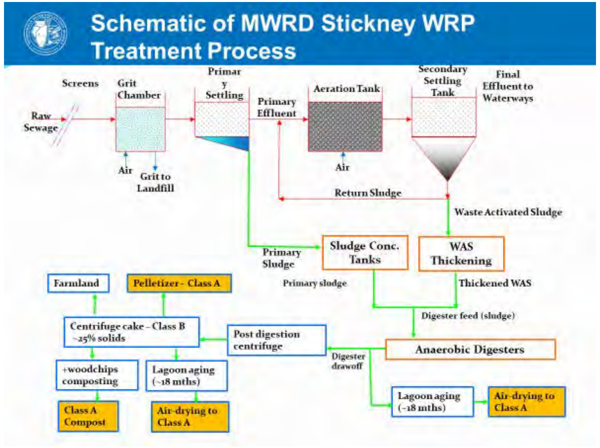
– Flue gas cleanup

– Environmental remediation

– Medical waste sterilization

6. Workshop on Application of Electron Beam (EB) Technology to Wastewater and Biosolids Treatment

- One of the main barriers to implementation of the technology is lack of information.
  - A book chapter is needed Current water and municipal wastewater treatment technologies
- Review of previous efforts on using e-beams to treat wastewater and biosolids
  - Including ability to remove different contaminants like PFOA, MTBE, PCBs, and pharmaceuticals
- Economics of wastewater and biosolids treatment
- Industrial current state and future opportunities for e-beam accelerator technology



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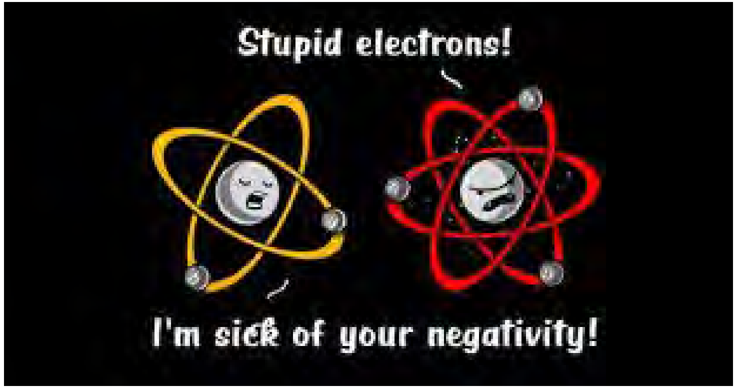

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