Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

Developing Accelerators for Energy and Environment at the Illinois Accelerator Research Center (IARC)

Bob Kephart,

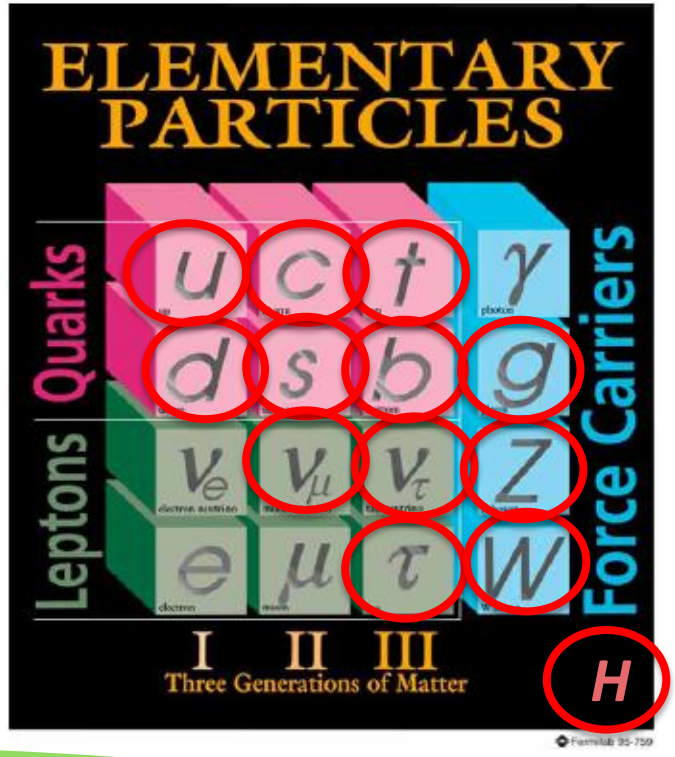
APT seminar

Fermilab Nov 2014

At Fermilab we build state-of-the-art accelerators to understand our world via Particle Physics

- Accelerators have enabled the construction of the Standard Model of the visible world (39/141 Nobel Prizes since 1939)

Rich history of discovery:



- Discovery of antiproton showing matter-antimatter symmetry
- Discovery of J/Psi meson (charm)
- CP symmetry is violated
- Discovery of two types of neutrinos
- Discovery of W, Z bosons responsible for the weak force
- Discovery of 3rd generation leptons

FNAL

- Discovery of bottom and top quarks and flavor mixing
- Discover of the Higgs Boson (origin of Mass)

CMS

Fermilab

Discovered with an Accelerator

Despite their impact on science, most accelerators that have been built are used for other purposes

- About 30,000 accelerators are in use world wide
  - Sales of accelerators > $ 2 B /yr and growing
  - Accelerators touch over $ 500B/yr in products
  - Major Impact on our economy, health, and well being

- Some Products:

Shrink wrapped food

Radial Tires

Digital Electronics

Aircraft

Current Accelerator Applications

Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties

Semi Conductors

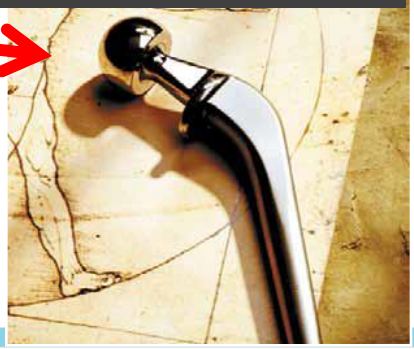
- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

Applied Materials, Inc.

Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

N2 ions reduce wear and corrosion in this artificial femur



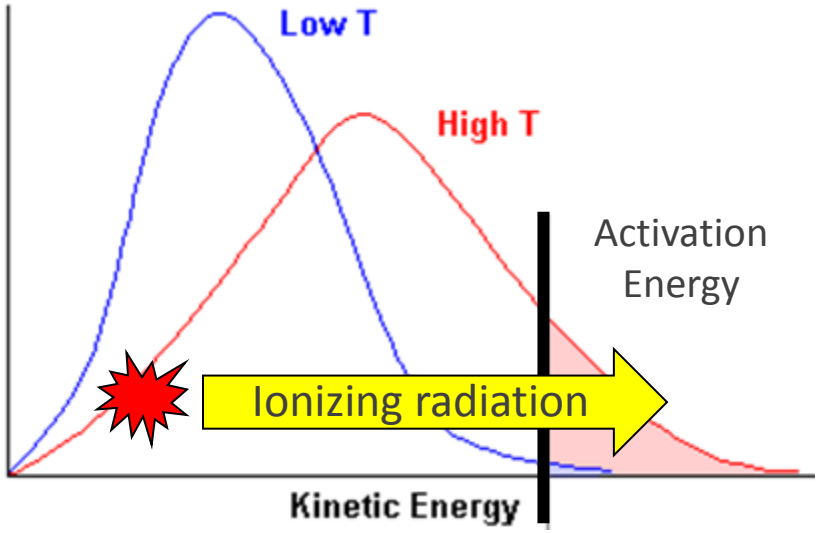
Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!

Accelerator Driven Chemistry

Radiation energy is different from Thermal energy !

Thermal energy **is very strongly coupled to Translational, Rotational and Vibrational modes of the energy absorber. Ionization, bond rupture and other processes leading to chemical reactions occur only in the high energy region of the Maxwellian tail.**



Ionizing radiation **is almost entirely absorbed by the electronic structure of absorber, which increases the energy level of its orbital electrons.**

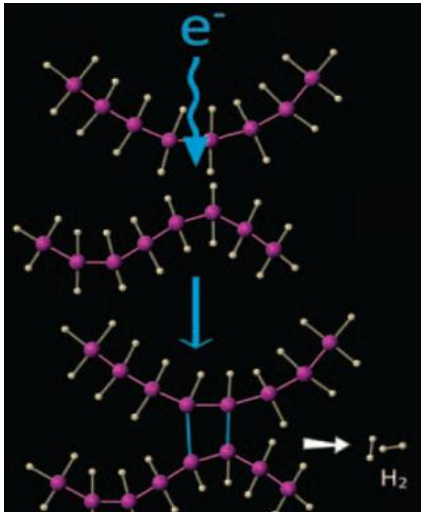
Energy in the form of large quanta have more pronounced chemical effects than energy in the form of small quanta (ie processes can occur at lower temperatures ➔more efficient!)

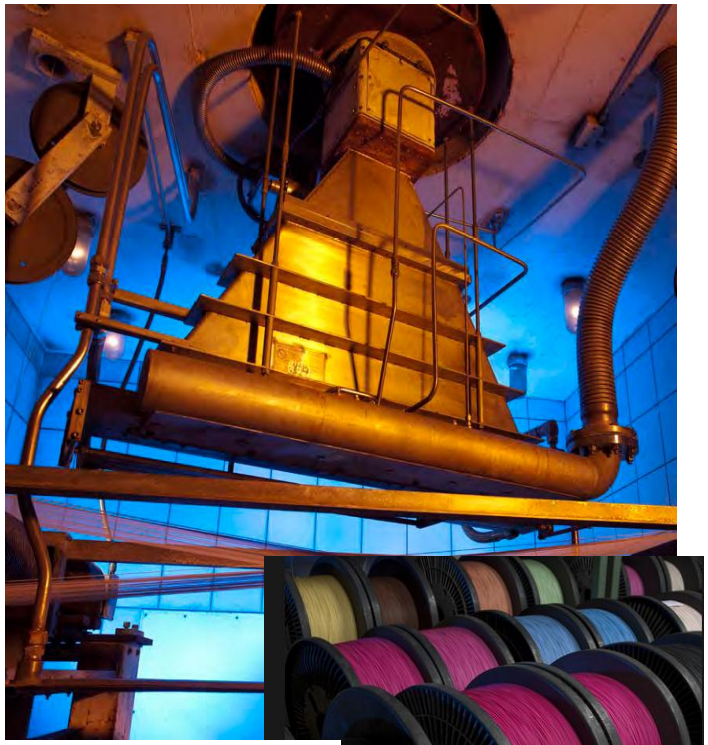
.Effective & efficient generator of reactive species

Accelerators: Essential Tools in Industry

A wide-range of industrial applications makes use of low-energy beams of electrons to drive chemistry

- 0.1-10 MeV up to MW beam power electrostatic, linac, betatron accelerators





Electron Beam Irradiation

Improved heat resistance of coatings, wire and cable, crosslinking polymers, radial tires, etc)

1500 dedicated facilities worldwide

Fermilab

Accelerators: Essential Tools in Industry

Electron beam printing

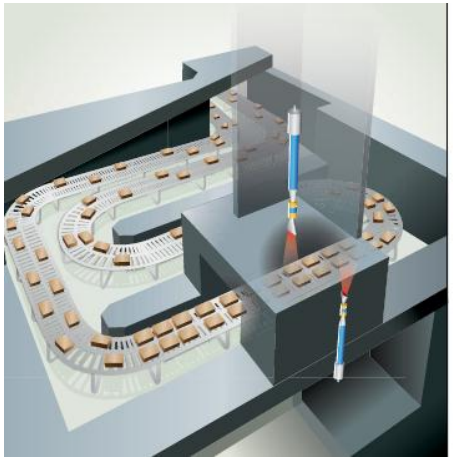
- Conventional printing requires use of enormous amounts of solvents that are created, evaporated, and must be disposed of … all with significant environmental impact
- EB printing can print 12 colors at 600 M/min with water based inks
- EB's also enables new packaging methods for food (foil-glue-foil)
- Your milk carton or potato bag may have been manufactured with this technology

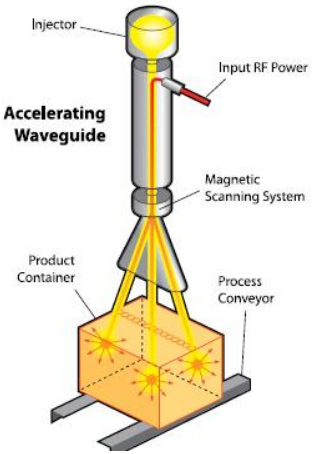
Electron Beam Packaging

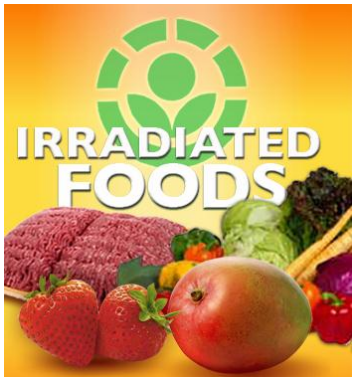
Accelerators: Food Preservation

Low-energy beams of electrons can help beat food-borne Illness

- ~6000 people/week are sickened, and ~100/week die from food-borne illness in the U.S.
- Food poisoning is estimated to cost the US $152 billion a year.
- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef, milk, juice, military rations…
- Many more opportunities exist
- Barriers = cost & public acceptance



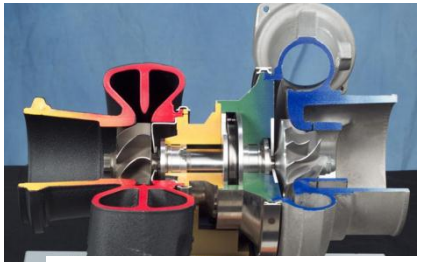




Fermilab

Accelerators for Industrial Processes

Fuel injectors



Turbo chargers

Weld gear boxes
Harden gears

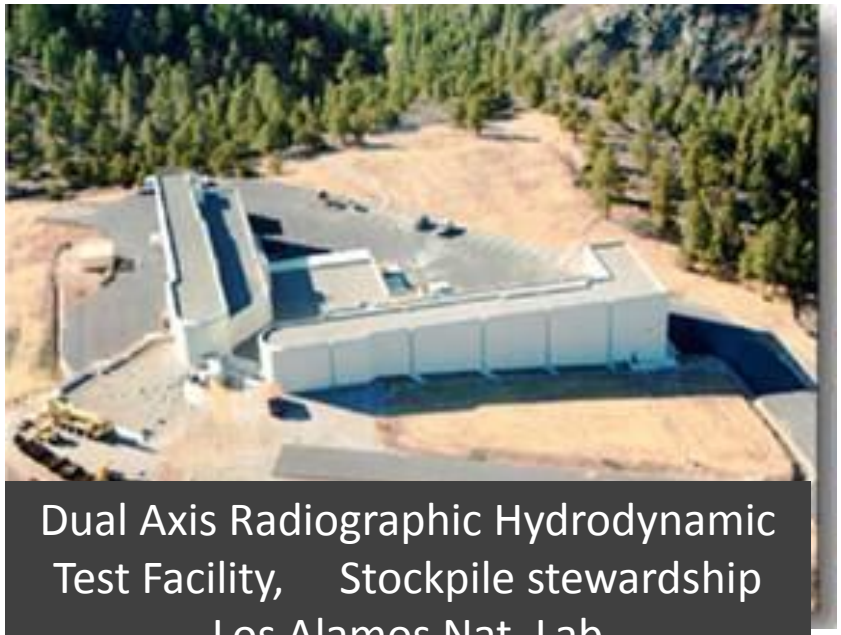
Electron Beam Welding and Machining

- Deep welds, low weld shrinkage
- Dissimilar or refractory metals, etc
- Widely used in automotive and aerospace industry
- Drill 3000 holes/sec!

PAVAC Energy Corp

Jet engines &
Gas turbines

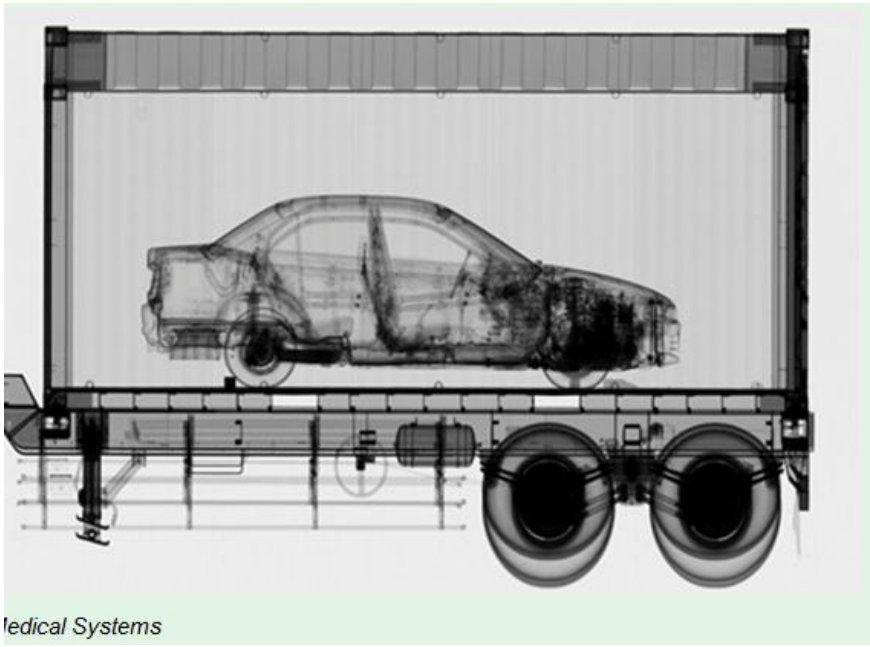
Accelerators for Defense



Dual Axis Radiographic Hydrodynamic Test Facility, Stockpile stewardship
Los Alamos Nat. Lab

- Proton Radiography LANL: Imaging materials in motion using x-ray and particle beams

Accelerators for National Security



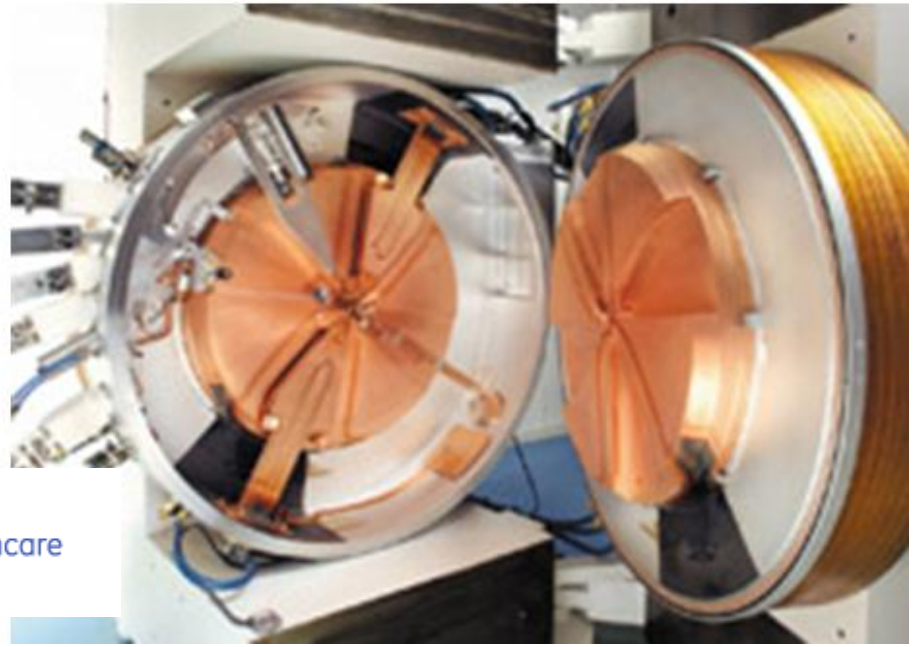
- More than two billion tons of cargo pass through U.S. ports and waterways annually.
- Accelerators are used for cargo scanning and “active interrogation” to detect special materials

Accelerators in Medicine

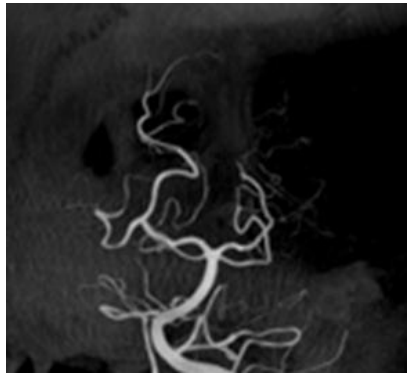
Electron accelerator
Based X-Ray facility
For cancer treatment
(Varian Medical systems)

Rhodotron, commercial
electron beam accelerator used
For sterilization of medical devices

Accelerators for the Medical Isotopes



- "Turn key" cyclotrons produced by industry are routinely used to produce short lived radio-pharmacy isotopes for molecular imaging (^{18}F, $^{11}CO_2$ $^{11}CH4$, ^{13}N, ^{15}O, etc)
- PET =Positron Emission Tomography



Accelerators in Medicine

Proton Cancer Therapy

Loma Linda Proton Therapy and Treatment Center

World's 1st proton accelerator built specifically for proton therapy

Designed and built at Fermilab

Technology Demonstration → Industry

New compact SC magnets (another HEP technology!)➔ smaller size/ costs →

Fermilab

The Opportunity for Fermilab

- In pursuit of our HEP mission FNAL:
  - develops & operates high energy, high power (MW), high reliability accelerators;
  - host largest U.S. accelerator complex; and
  - employs 650 FTE staff in the "accelerator sector ~ 300 accelerator scientists and engineers (+ more at nearby ANL)
- Fermilab (and Northern Illinois) has the largest collection of Accelerator experts in North America
- We build accelerators for a living….
- IARC = opportunity to use our staff and capabilities to have a large impact on future industrial accelerators and applications

Future Accelerator Applications

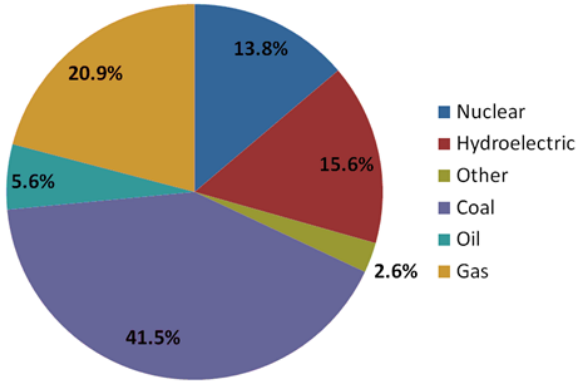
Many Opportunities!

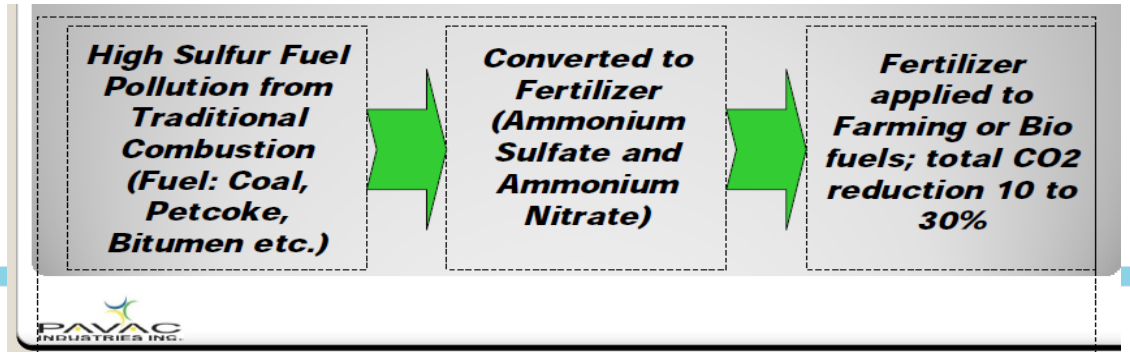
Sector	Opportunities
Energy and Environment	• Flue gas treatment • Gas to liquids conversion and flare gas recovery • Upgrade of heavy oils • Superconducting wind generators • Accelerator driven power plants, Nuclear waste destruction • Waste Water and sludge treatment
Industrial	• Next generation semiconductor fabrication • Food preservation and safety • Improved welding and fabrication (3D metal printing) • Improved Highway construction • Materials transformation/processing • Industrial isotopes as wear indicators, etc
Medical	• Accelerator-driven medical isotope production • Particle beam cancer therapy
Safeguards and Security	• Non-invasive and stand-off inspection

- Some of these new applications will create entire new industries
- A bit more on some of these…

Accelerators for the Environment: Coal

- 41% of all electrical power worldwide is generated by burning coal
- China and India are ramping up use
- US EPA regulations will reduce coal but it will remain an important energy source
- Emission of NOx and SOx is a serious environmental issue
- Accelerators can treat flue gas turning NOx and SOx into fertilizer
- 1st step towards sequestration of CO_2



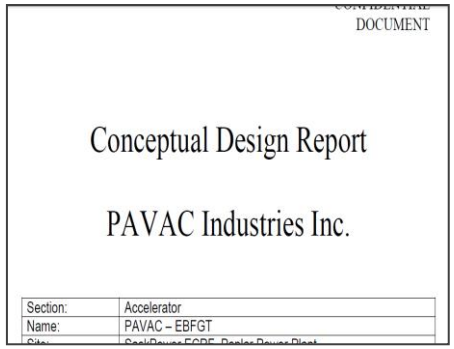


Accelerators for the Environment: Coal

- Current economics favor natural gas. However use of coal is projected to stabilize and remain a significant source of U.S. & world electrical power
- New EPA standards require low SOx and NOx emissions
  - Current solution is SCR scrubbers (~ 6% parasitic load)
  - EBFGT may have the potential to reduce this load to 3%
  - Effectively also lowers carbon emissions of the plant
- Fermilab has teamed with PAVAC Energy Corp to develop EB Flue Gas Treatment
  - PAVAC = Vancouver B.C. & Batavia, IL
- PAVAC is funded by Canadian sources to locate an test accelerator on a coal fired plant in Saskatchewan

Accelerators for the Environment: Coal

- Under proprietary contract from PAVAC:
  - Fermilab designed a 500 KW, linac
  - Pulsed RF Cu linac; solid state PS
  - High beam loading allows high efficiency
  - Fabrication is in progress at PAVAC. (attention to costs!)


DOCUMENT

Conceptual Design Report

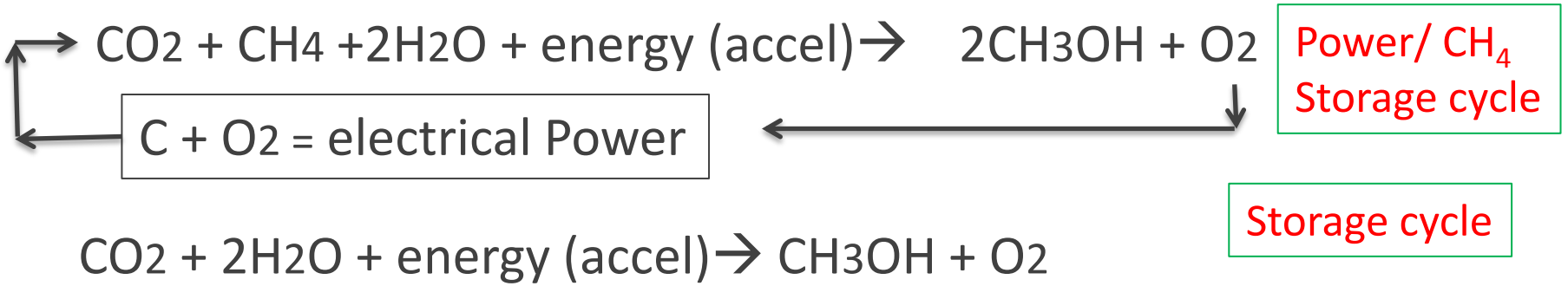
PAVAC Industries Inc.

Section:	Accelerator
Name:	PAVAC – EBFGT

- Fermilab and PAVAC are currently seeking funding to build an EBFGT development and test facility at IARC
- Goals are optimized accelerator efficiency and reliability
  - Also process improvements & improved economics
  - Low parasitic load & reagents/byproducts are key since pollution control represents 1/2 the plant operating cost
- Such an accelerator has many other possible uses

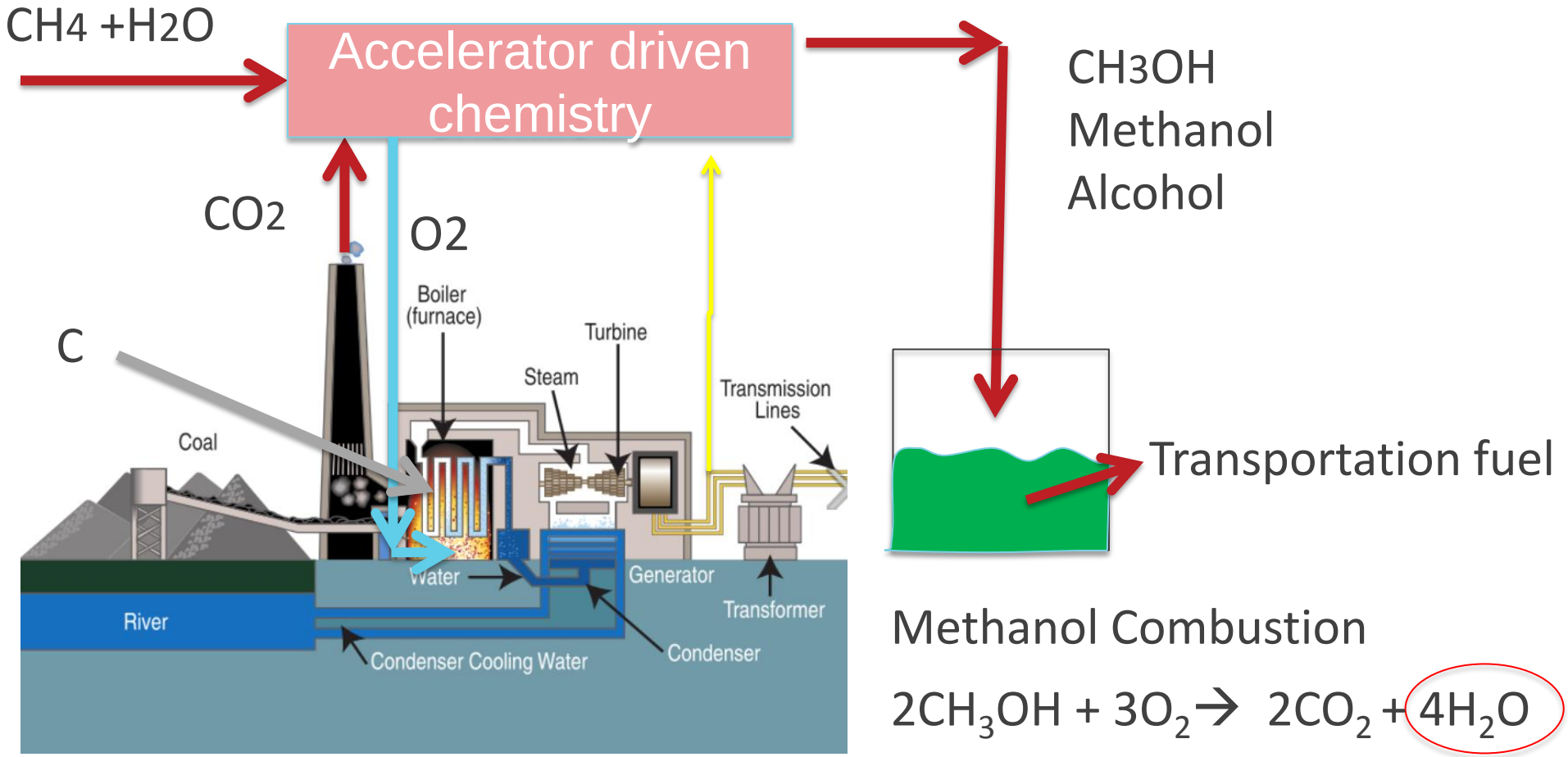
Accelerators for the Environment: Carbon Reuse

- Coal fired plants are major sources of man made $C0_2$
- In addition to removing NOx and SOx accelerators and abundant natural gas in the U.S. provides an opportunity to reuse the CO_2 reducing overall emissions and creating methanol for transportation fuel and/or for chemical feed stocks (lower overall emissions)
- Alternative paths for storage of energy produced by renewables (e.g. wind or solar), a key problem that must be solved to allow widespread use. Example reactions:



Accelerators for the Environment: Carbon Reuse

- Emission free coal plant (no NOx, SOx removed via EBFGT)
- Carbon reused as Methanol for transportation fuel



Accelerators for the Environment: Flare Gas

- Many wells produce both oil and natural gas, but not all gas is recoverable
  - Remote, so pipelines are not economical
  - Produce a burst of gas for only a few years
  - Methane is a powerful green house gas… so most companies "Flare" stranded gas at the well
- World wide $ 30 B/yr of gas is flared
  - Equal to 25% of the natural gas usage of U.S.
  - **Adds CO_2 with no useful work for mankind**
- "Fischer-Tropsch" can convert gas to liquid hydrocarbons but requires large plants for high temperature/pressure reactions
- Mobile accelerators could in principle break C-H bonds to efficiently convert stranded gas to liquid hydrocarbons at the well head, could also lower viscosity of heavy oils

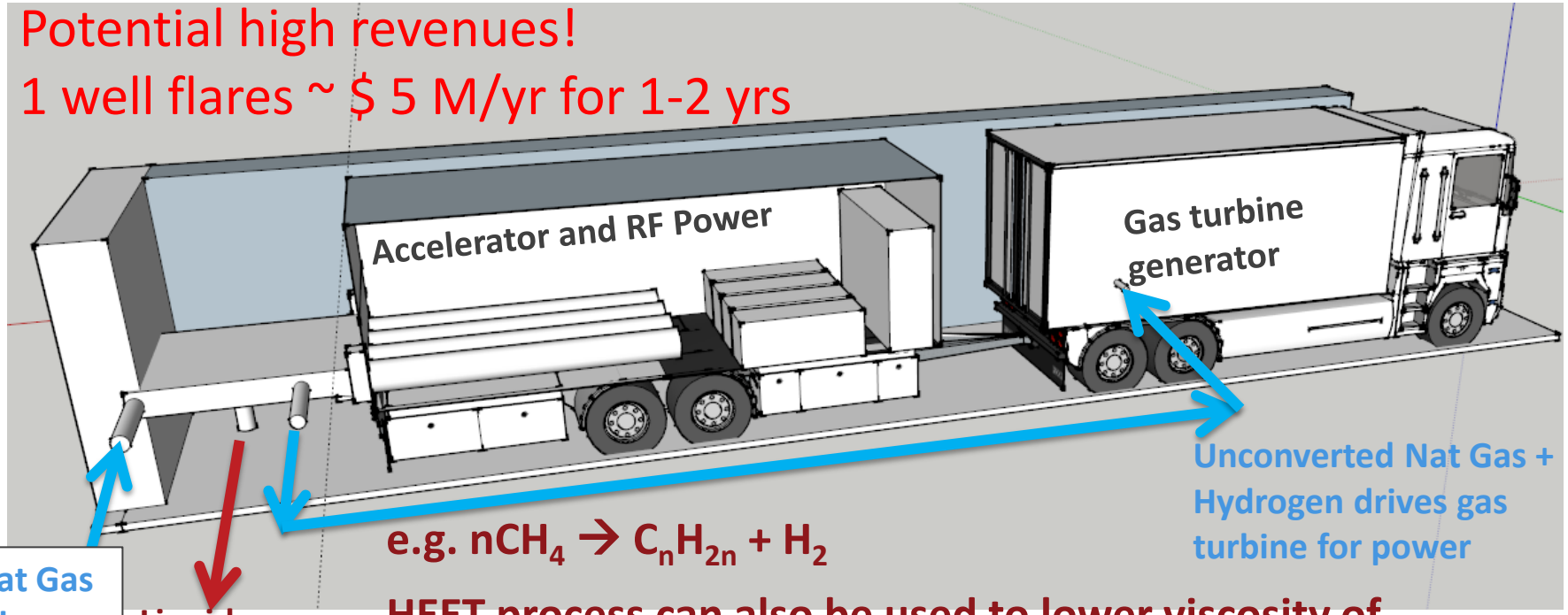
Gas flares in ND

32% is flared!

Fermilab

Accelerators for the Environment: Flare Gas

- Trailer mounted high power electron accelerators
- Natural gas turbines provide the local electrical power
- Liquid hydrocarbons created can be mixed and collected with crude oil produced by the well



Fermilab

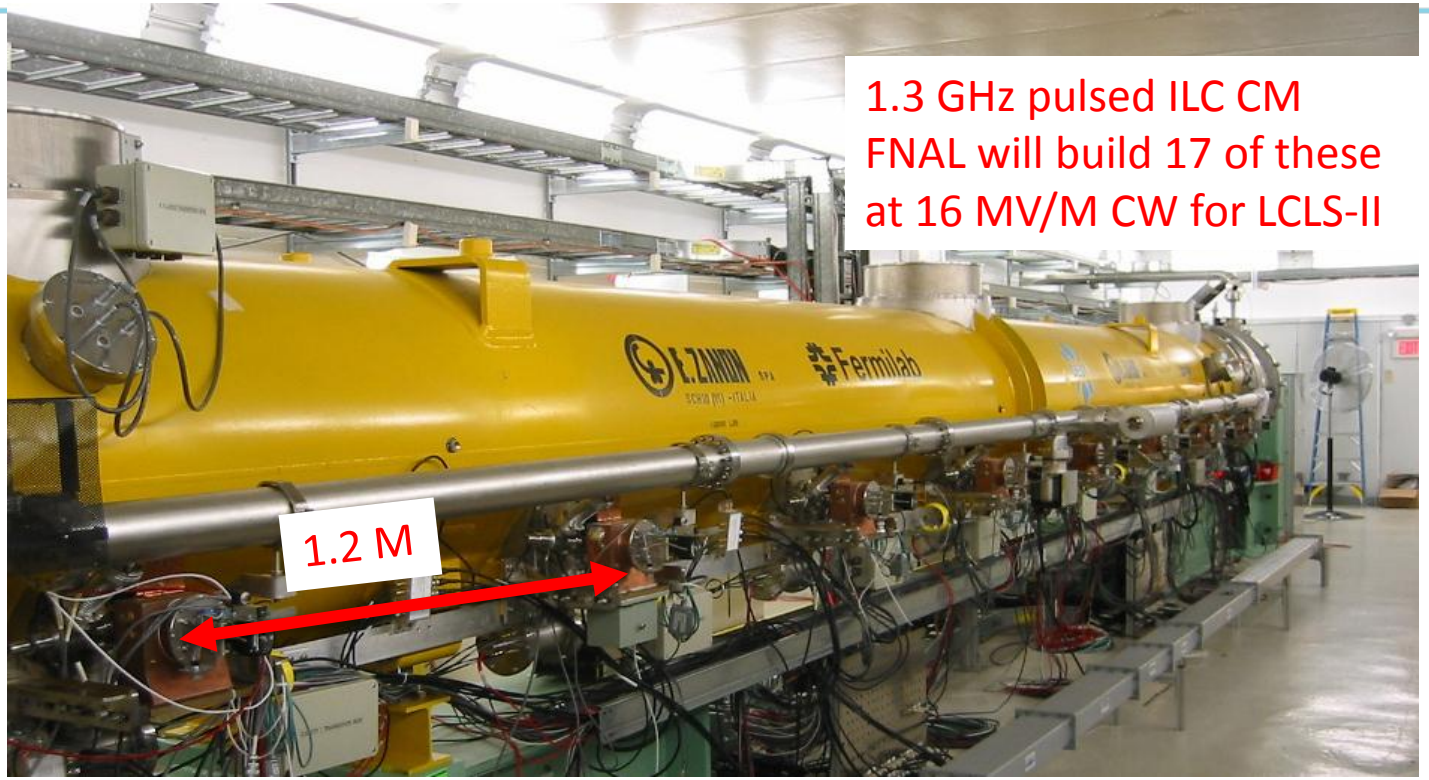
Accelerators for the Environment: Water/Sludge

- Electron accelerators are effective for
  - Destroying pesticides, organics, pharmaceuticals, etc in water
  - Treating industrial/municipal water/sludge
  - Sewage Sludge Sterilization

SRF is Compact!
400 KW = 10 MeV, 40 mA
Q_0 = 7 x 10^{10} @2K

- However, despite R&D demonstrations the market penetration of this technology is limited
- Why?
  - Municipalities = conservative users, not able to finance R&D
  - Deployment likely to be regulatory driven (tricky for business)
  - Reliable, compact, high power (MW class), efficient (wall plug to EB power), cost effective accelerators are needed.
  - Turn key MW Accelerator development requires $ + extensive infrastructure… who will fund deployment? SRF?

Enormous Progress in SRF in the last decade



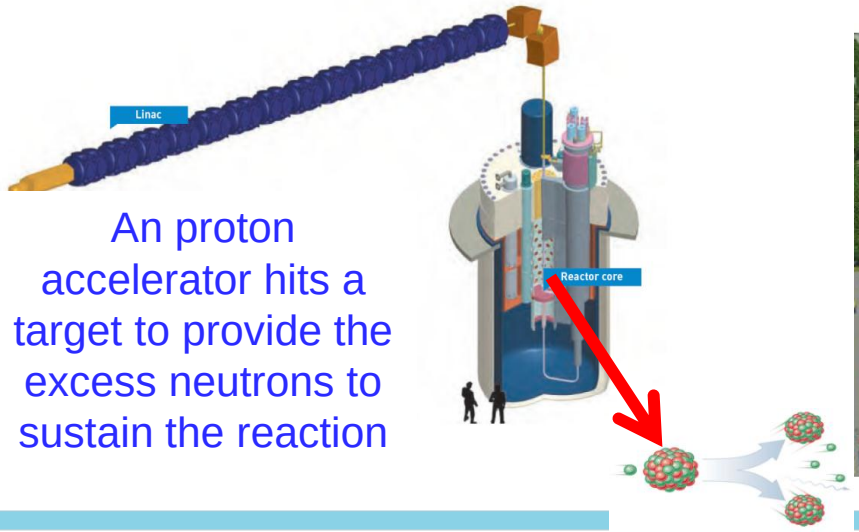
- 8-cavity Cryomodule at Fermilab: Tested at 31.5 MV/M
- 250 MeV in 10 meters ! (very compact)
- New developments in RF sources : precise phase & amplitude control of magnetron: ($10/KW vs $ 10 per watt for SS)

Accelerators for the Environment: Water/Sludge

- Fermilab has begun discussion with several companies
  - 1st step: Viable Business Plan: including market analysis, customer base, fundamental obstacles to widespread use
  - 2nd step: Design a compact, efficient, turn-key accelerator
    - leverage development from “high return” applications
  - 3rd step: 1st real customer.. Likely at a pristine site with a eco-conscious partner with $ and who is not risk adverse
    - e.g Aspen Colorado, Naval Base + funding via a grant !
  - 4th step: commercialization & marketing of a turn-key system to a “big” customer (e.g. City of Chicago)
- Keys to success:
  - Federal and State funding for development of cost effective and scalable systems developed for other applications
  - Regulation or water shortages may drive outcomes

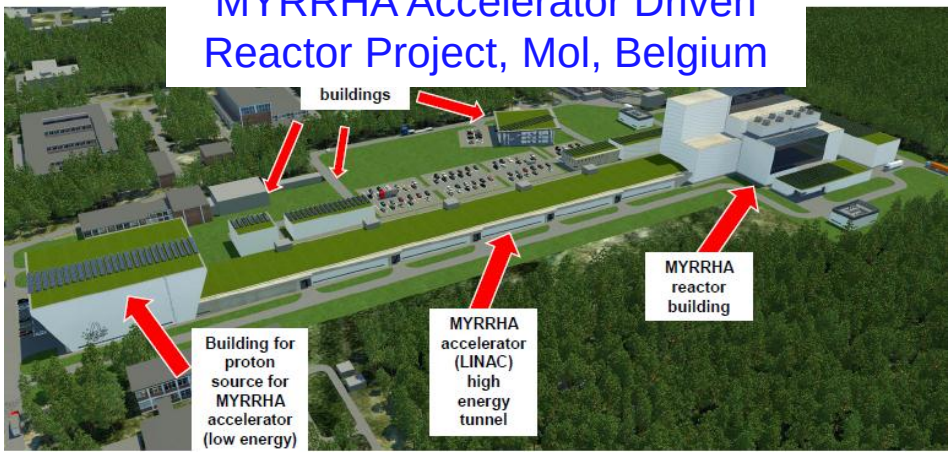
Accelerators for Energy: ADS

- **Accelerator Driven Subcritical Reactors** can transmute nuclear waste so it is much safer and simpler to store, while at the same time generating electrical power
  - Subcritical reactors ➔ Safety… Accelerator off ➔ reaction stops…no run away reactions !
  - Requires very high beam power (>10 MW) and very high reliability
  - This technology is actively pursued in Europe, China, India



An proton accelerator hits a target to provide the excess neutrons to sustain the reaction

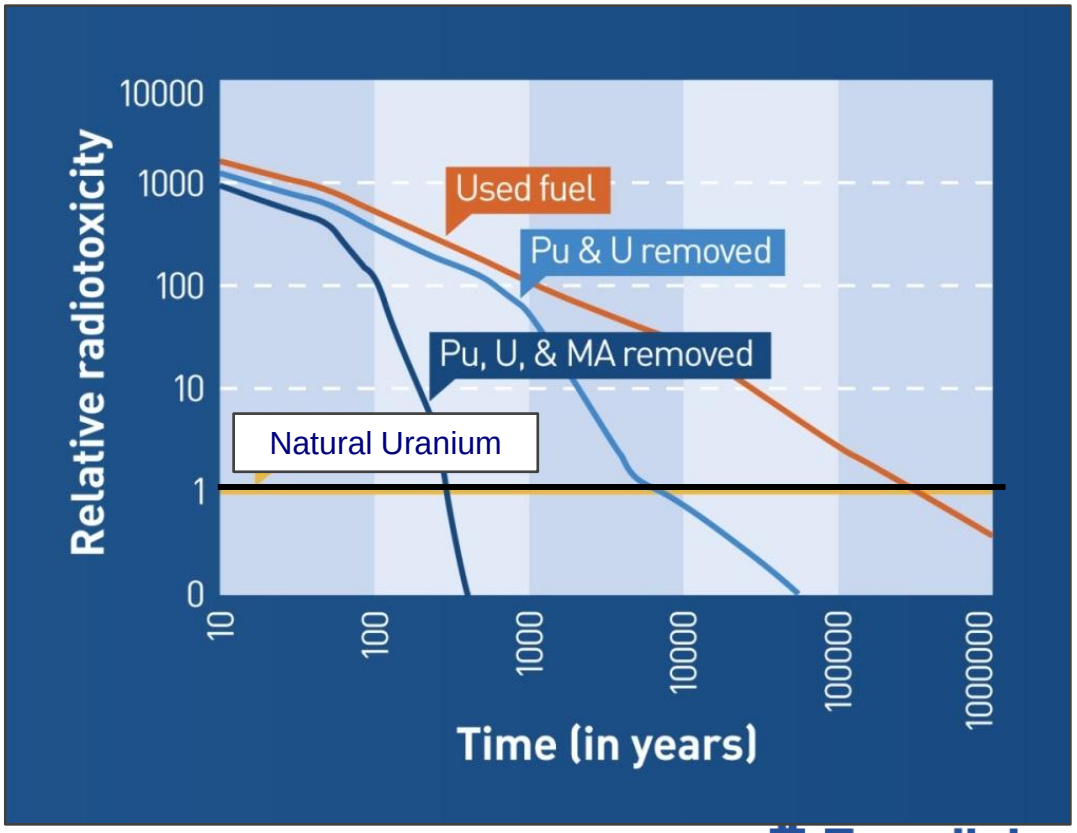
MYRRHA Accelerator Driven Reactor Project, Mol, Belgium



Accelerators for Energy: ADS

Accelerator based transmutation combined with geological disposal has the potential to make nuclear power, a zero carbon energy source, acceptable to society

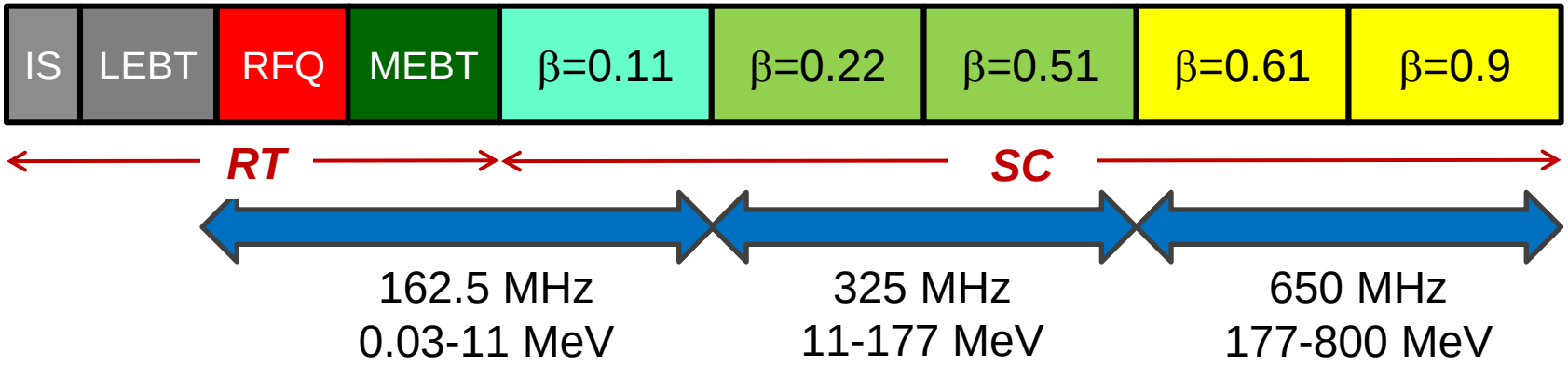
- ADS can also potentially make use of non-fissile fuels like Thorium
- Superconducting RF Linac's can provide high beam power & efficiency
- Molten salt sub critical reactors may make this even more attractive



ADS and Fermilab

- **PIP-II (Proton Improvement Plan –II)** is a project to significantly increase the intensity of the Fermilab accelerator complex via the addition of a 800 MeV Superconducting Linear Accelerator. (in support of the neutrino science program)
- Construction of PIP-II was recently strongly endorsed by the High Energy Advisory Panel in its long plan for the field
  - A strong R&D partnership exists with India for joint development of SRF for this accelerator (RRCAT, BARC, VECC, IUACC)
- An active R&D PIP- II R&D program has been ongoing for many years, construction of PIP-II strongly supported by P5
- In addition to Physic Research, PIP-II is designed to provide simultaneous beam to a 1 MW class ADS test facility.
- PIP-II can enable an ADS development facility… <u>if funded</u>

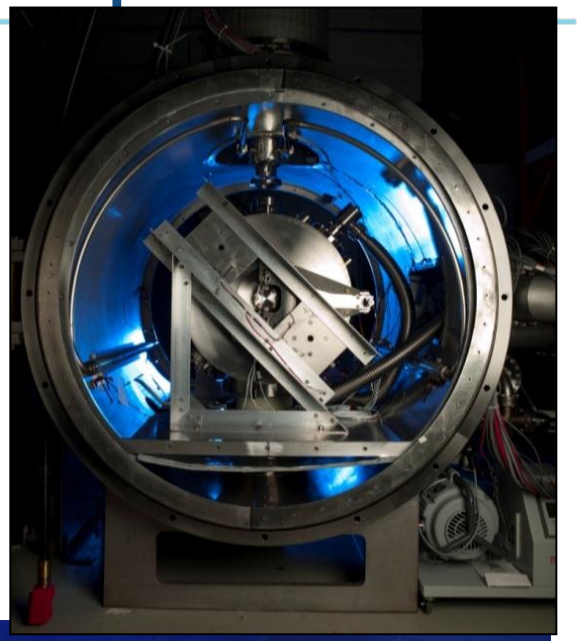
PIP-II Linac Technology Map

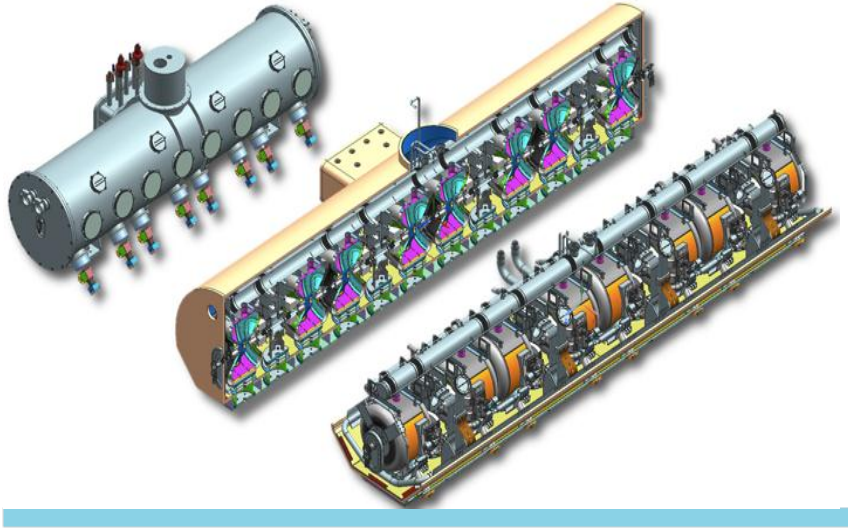


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

All components CW-capable

Some of the PIP-II SRF cavities under development





Fermilab

New FNAL SRF infrastructure


VTS

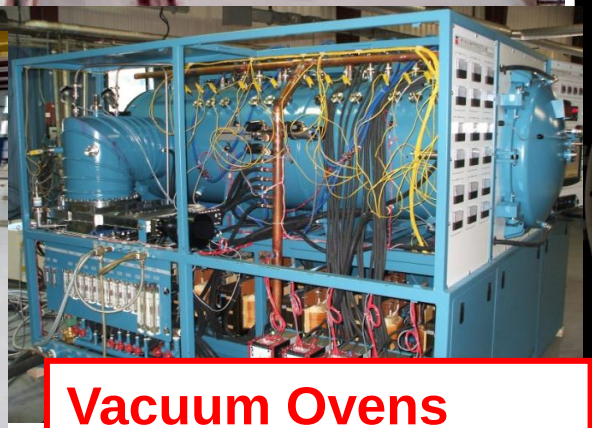

Clean Rooms


MP9 Clean Room


New Cryo Plant

New Valve Box


Cryomodule Assembly


Vacuum Ovens


STF

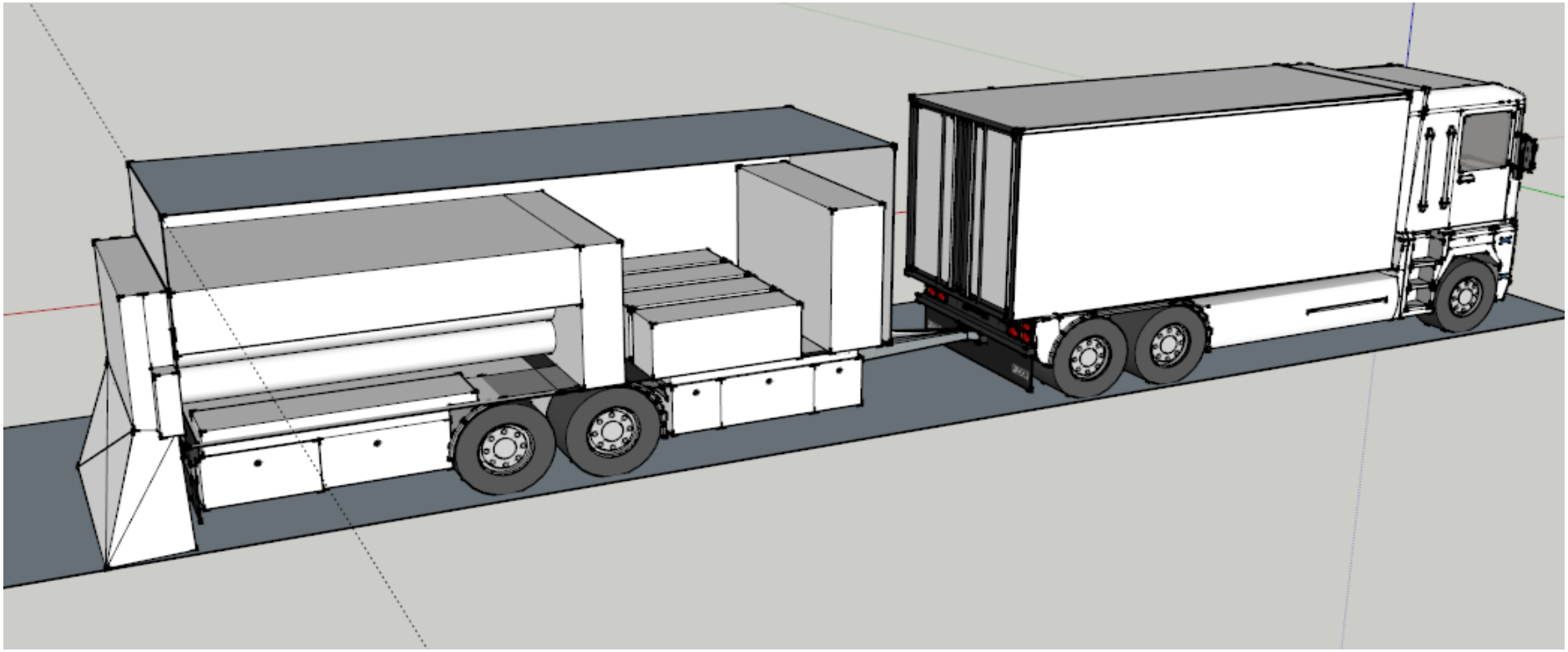
Accelerators for the Environment: Highway Life Extension

- Realization # 1: New technology allows the construction of compact, high power, high energy, high efficiency electron linacs
- Realization # 2: It is possible to make these high power EB sources mobile allowing new applications
- Realization # 3: EB treatment can significantly improve the materials properties (e.g. toughness, low temperature performance) by crosslinking
- 1-3 mean that that field crosslinking of building materials is now feasible “in principle”

Accelerators for the Environment: Highway Life Extension

- 2.3 million miles of paved roads in the U.S.
  - 94% are constructed from asphalt, technique little changed in 100 yrs
  - Average road must undergo major repair, crack and pothole repairs every 1-3 yrs and must be completely rebuilt every 5-8 yrs depending on the climate
  - The U.S. places 550 million tons of hot mix asphalt each year at a cost of $ 25 B/year to taxpayers
  - The heavy machinery used to rebuild asphalt highway creates a huge carbon foot print.
- Even a 1 yr extension of life of a road would save enormous amounts of diesel fuel and taxpayer dollars each year
- Solution: Crosslink binder (bitumen+?) in situ with mobile accelerator
  - increase strength and toughness.
  - Assume this requires 100 kGray (conservative)

Mobile EB to extend lifetime of highways



- 4 accelerators: 1400 KW ➔ 2 lane-miles per 8 hr shift
- Cost of 1 lane-mile interstate highway = $ 2.4 - 6.9 M
- Huge value added ~ $ 500 K- $1.4 M per shift (1 yr extension)
- $ 5-8 M capital cost ➔ very short payback period!

Fermilab

Can one generate the required power with a mobile generator?

- Yes: diesel or gas turbine based generators > 5 MW fit into a standard over the road trailer
- New 3 MW units ~ $2-3 M. used ~$ 500 K

3 Unused Kongsberg/Viking KG5 3MW 50Hz or 60Hz 2740kW DF Mobil Power Plants

Accelerators for the Environment: Highway Life Extension

- Status:
  - Fermilab has filed for patent
  - Developing designs for the required accelerators
  - Shielding is a challenge, but simulation ➔ solvable
  - Engaged in process development using commercial irradiation facilities including examination of the benefits of various additives to bitumen vs alternatives
  - Goal is to be able to use all current road building equipment and treat the new asphalt before first use.
- Longer term
  - Team with large industrial partner
  - Fermilab's site contains many miles of asphalt roads and can serve as an ideal testing ground (e.g. no permits required)

Accelerator Technology Applied to Wind Turbines

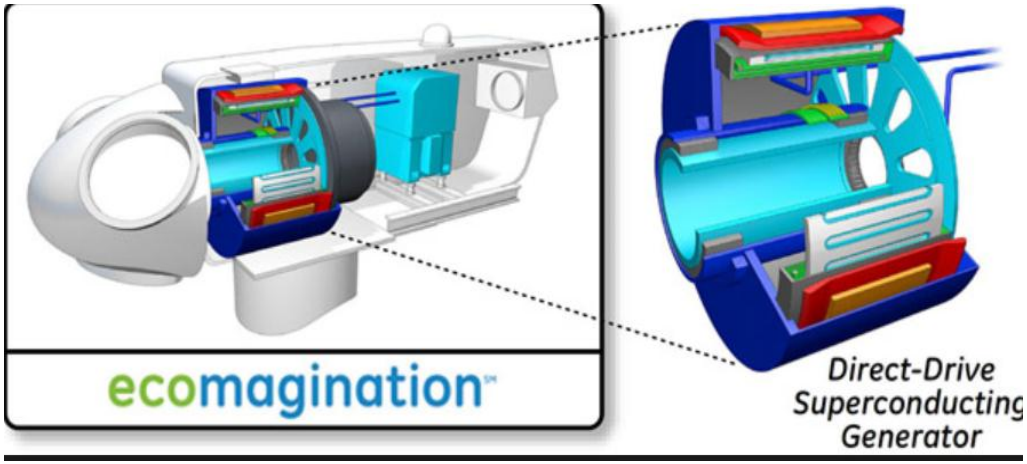
- Superconducting Magnet Technology developed for high performance accelerator magnets is being applied to create novel SC generators for wind turbines

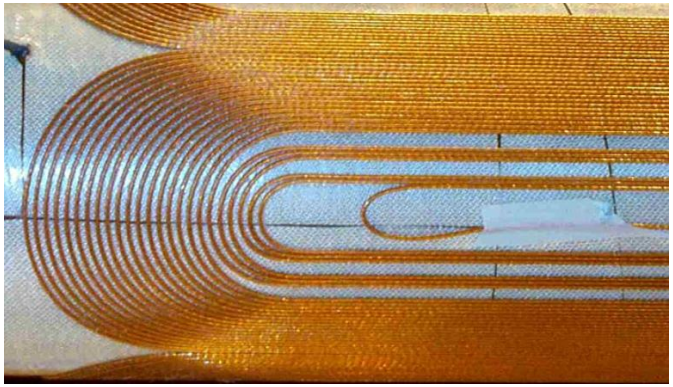
Accelerator Technology Applied to Wind Turbines

- Why is Accelerator Technology Relevant?
- The size of wind turbines is currently limited by the “head weight” of the gearbox and conventional generators.
  - Current production devices are in the 2-5 MW range
  - Gearbox reliability is an important issue
- SC generators can have much higher power densities and require NO gearbox.
- This can allow wind turbines in the 10-25 MW range
  - Bigger Higher towers = more wind, steadier wind
  - Ideal for Off Shore applications
  - Operation at 4 K with NbTi conductors looks practical using current technology

Accelerator Technology Applied to Wind Turbines

- Generators built with new technology based on high temperature superconductors like Nb_3Sn have great promise
  - allow operation at higher temperatures simplifying designs and making them lighter and more efficient (e.g. 10 K operation)
  - Cryogen free (e.g. closed cryocoolers) Self starting
  - Conductor, Coil designs, insulation and curing technology, etc developed for High Energy Physics can be directly applied
- HTS may eventually allow operation at LN2 temperatures





Great ideas… So what is the Problem?

- New applications of accelerator technology seem to die for one of four reasons
  - Feasibility not proven: Inadequate resources: (financial, personnel, infrastructure) in industry, universities, or labs to demonstrate the basic feasibility of an idea
  - During transition from small scale technology demonstration to a commercial product (may require large investments & infrastructure)
  - Judged not economically viable reliability of technology, capital investment required, or operating costs not demonstrated vs other approaches
  - Lack of acceptance of the new technology by potential customers that is cured only by large scale demonstrations that lower perceived risk and demonstrate costs
- A new Facility being built at Fermilab (the Illinois Accelerator Research Center) is intended to help fill these gaps by providing access to accelerator experts and laboratory infrastructure

Illinois Accelerator Research Center

IARC: What is it?

A New U.S. Center for Accelerator Applications under construction at Fermilab

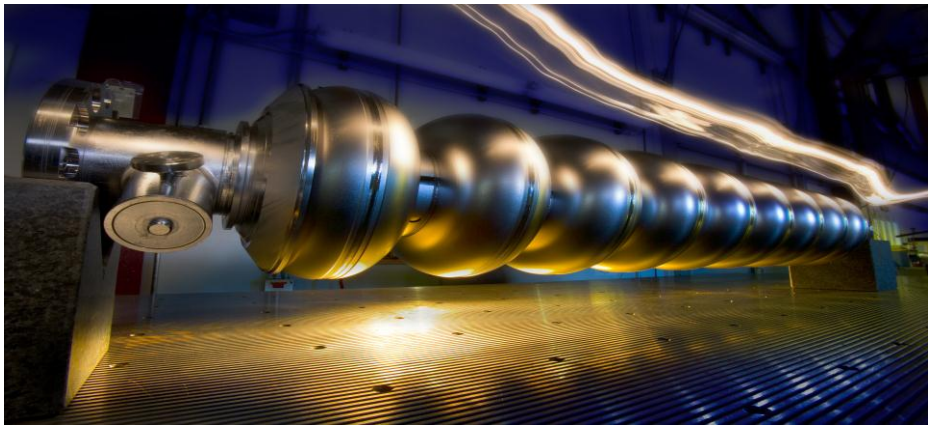
Why IARC?

- To enable Fermilab to work more closely with industry and university partners on Accelerator Technology Development and Accelerator Education
- To develop new accelerator technology based products and high tech industries in the U.S. (and especially in Illinois)
- IARC intended to be a portal for industry into the larger core capabilities and infrastructure at the lab

IARC Mission and Vision

Mission

Partner with industry to exploit technology developed in the pursuit of science to create the next generation of industrial accelerators, products, and new applications.



Vision

IARC will be the preeminent national enabler of accelerator based products and services serving as the seed for industry growth.

Illinois Accelerator Research Center

Construction Status

New State funded addition (white) is complete, now outfitting with partitions, furniture, partitions

1st occupants in Spring 2015

Fermilab

Role of IARC at Fermilab

Fermilab	IARC
Research Hub	Technology Development Hub
Single Program	Multi-Program
Basic Science/Discovery Mission	U.S. Competitiveness Mission
Funds Out (Procurements)	Funds In (new federal and state programs, Industry partnerships)
Nonproprietary Research	Patent/Copyright
Large teams, complex goals	Small teams, targeted goals
Federal standards and best practices	Industry standards and best Practices

Illinois Accelerator Research Center

Modern Design: Architects = Ross Barney

LEED Gold: Designed for Energy Efficiency

IARC: State funded building addition

48,000 gross square feet (lobby view)

IARC: State funded building addition

- One of two floors like this
- ~120 Offices total, Partitions, networks, furniture = DOE funds

IARC: State funded building addition

- Designed for IP protection (e.g. zoned IT networks, key card access)
- Next step is underfloor network and wiring to allow glass partition installation

52

IARC: State funded building addition

- One of two floors like this

IARC: State funded building addition

- Common space for lunch or coffee

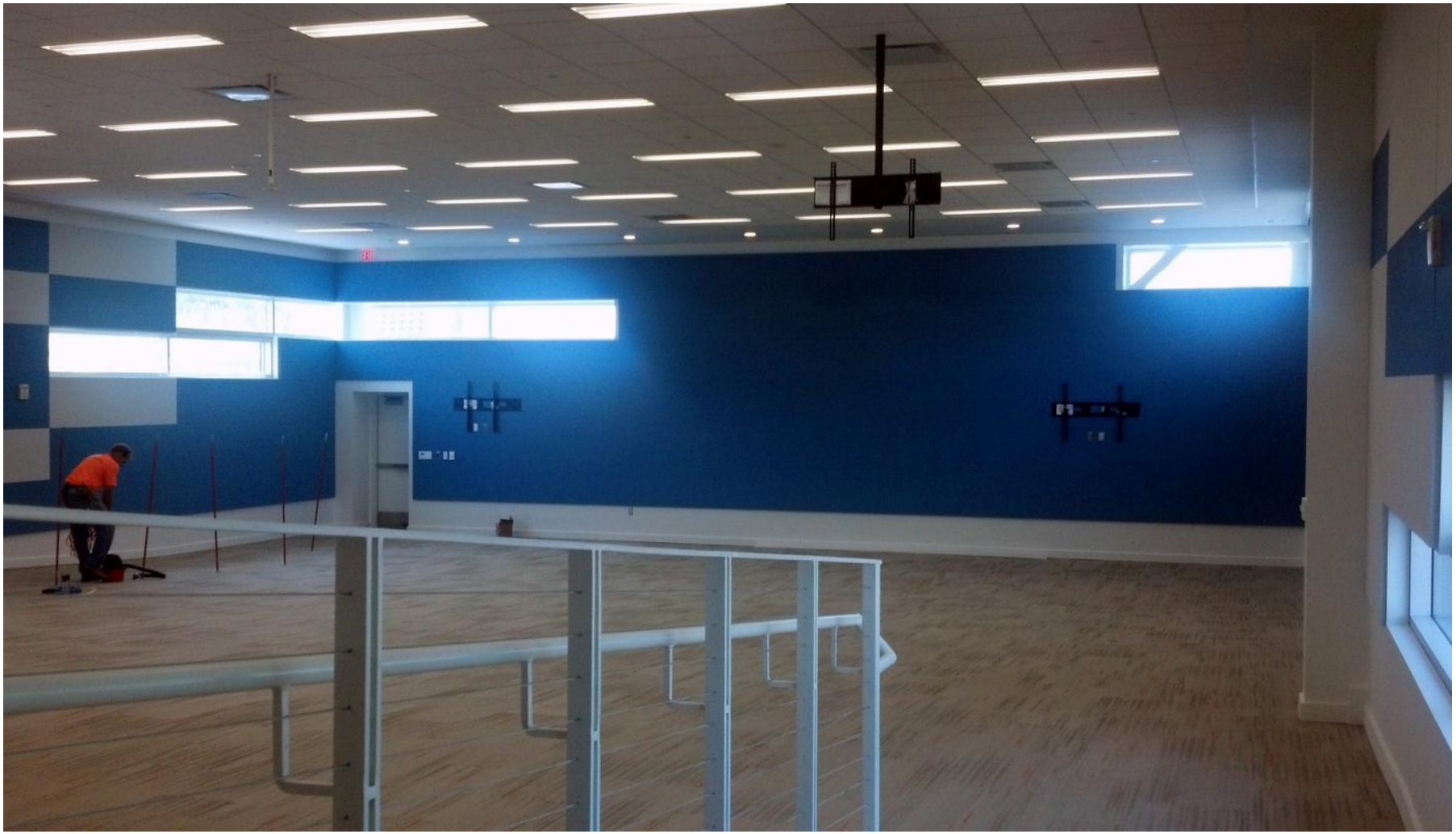
54

IARC: State funded building addition

- Green Roof, outdoor spaces , geothermal wells, lots of natural light, etc.
- Extensive of local and recycled materials

IARC: State funded building addition

- 175 seat meeting room, (Pier: Maximize bricks and mortar!)

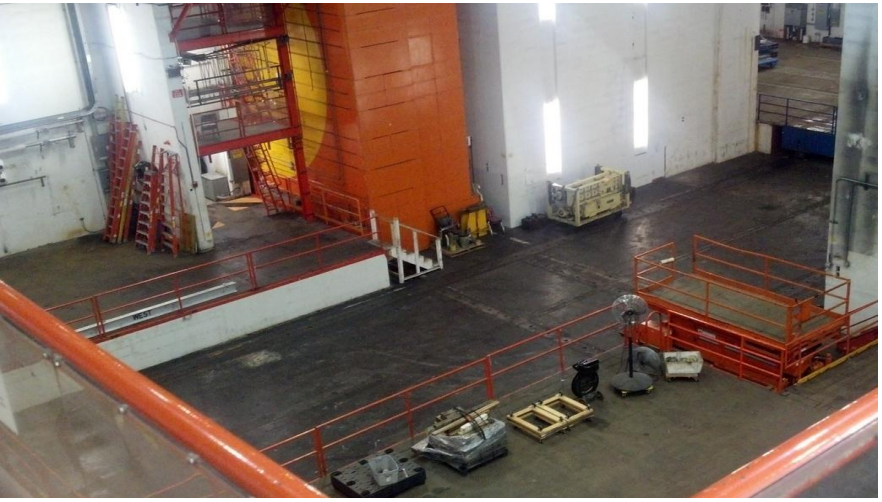


Fermilab

Heavy Assembly Building

- Used for the construction of the CDF experiment (42,000 sq ft)
- 50 T crane; 10 T crane
- Deep pit ideal for radiation shielding of high power accelerators;
- 1.5 MW of installed electrical Power (upgradeable)
- 2.0 MW of industrial, Low conductivity, and chilled water systems
- 600 W @ 4 K cryogenic refrigerator (upgradeable)
- Light tech space, machine shop, 40 offices, high speed IT network

What Industry Really Gets Excited About



- Building refurbishment in progress, available mid 2015

But IARC is more than a place

- It represents an unusual new partnership between DOE and the State of Illinois
- It also represents an experiment in expanding laboratory & DOE partnership with U.S. industry
  - Will serve as an industry portal to the large lab capability
  - Even before a formal program announcement we have been approached by > 20 industries interested in projects at IARC
- Goal is sustainability ➔ a business plan for each Project we launch (Development vs Research)
- Create products, applications, businesses that moves accelerator technology into the energy and environmental marketplace

Summary

- Fermilab is actively engaged in accelerator R&D in support of its basic science mission
- Much of the technology we develop can have applications beyond High Energy Physics
- With the completion of IARC, we plan to launch a large program of cooperative work with industry
- Many of these applications can have transformative impacts on the way mankind generates energy, and manufactures new materials.
- They can also have very positive effects on the environment for benefit of all mankind …. Our goal is all of this…
- AND to create new industries and jobs…

Extras

IARC Background

- FNAL realized that accelerator technology developed in the pursuit of science has an increasing economic impact
  - $ 2 B/yr in accelerator sales, touches $ 500 B/yr in products
- **2007: Proposal to the State of Illinois and DOE**
  - State: leverage Fermilab to create new industry in Illinois
  - DOE: Promote US industrial competitiveness
- **2009: Accelerators for Americas Future** symposium ➔strong support. Report: http://www.acceleratorsamerica.org/
  - Many applications are related to water, energy, environment
- **2010: IARC Project funded by the State of Illinois**
  - $ 20 M grant for a building addition
  - DOE agrees to Provide $13 M plus a refurbished heavy assembly building on the FNAL site (valued at $ 38M)
  - Together these will create a $ 70 M complex

IARC Background

- **2011 First DOE funding**
  - **President Obama emphasizes important of tech transfer from Federal Research to U.S. Industry**
  - IARC is well Aligned with National and HEP Priorities
- **2014 (May) HEP issued a RFI on: Accelerator Applications for Energy and Environment**
  - Expect 1st funding for Energy and Environment in FY15
- **2015 IARC facility ready and formal launch of IARC Program**
  - **Business entity reviews all R&D programs to insure that a practical business plan for deployment exists**
  - **Sustainable: revenues support future projects**