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Review of Potential Accelerator Systems for Energy and Environmental Applications

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Argonne National Laboratory
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Workshop on Energy and Environmental Applications of Accelerators

U.S. DEPARTMENT OF ENERGY | Office of Science

Workshop on Energy and Environmental Applications of Accelerators

June 24–26, 2015

- **Co-Chairs:** S. Henderson, T. Waite
- **Invited Participants:** L. Cooley, W. Cooper, C. Cooper, R. Curry, R. Eichhorn, S. Golhar, S. Gourlay, T. Granato, J. Hirshfield, M. Kemp, T. Kroc, D. Larbelestier, P. Masson, P. McIntyre, D. Meeroff, J. Minervini, J. Nolen, P. Ostroumov, S. Pillai, J. Power, R. Rimmer, D. Staack, P. Tornatore, V. Yakovlev
- **Observers and Other Participants:** J. Bray, B. Brobst, D. Brown, A. Chmielewski, E. Colby, J. Cotruvo, R. Galloway, T. Grimm, R. Hamm, B. Han, S. Hoboy, M. Johnson, T. Lerke, K. Marken, K. Olsen, C. Rey, S. Sabharwal, J. Smith, A. Todd, M. Tomsic,

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Accelerator Driven Systems White Paper Working Group

"Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"

http://science.energy.gov/~/media/hep/pdf/files/pdfs/ADS_White_Paper_final.pdf

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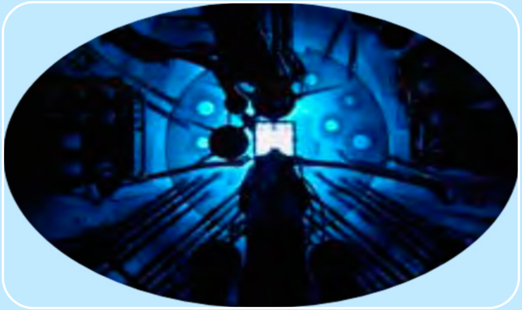
Landscape of Applications

Electron beam radiation processing

- Requirements: high power electron beams 0.5-10 MeV, with very high beam power > 100 kW
- Applications:
  - Water/sludge decontamination
  - Flue gas cleanup
  - Environmental remediation
  - Medical waste sterilization

Proton accelerators for advanced nuclear systems



- Requirements: GeV CW proton beams with 10's of MW beam power
- Applications
  - Transmutation of radioactive waste
  - Electricity production in subcritical reactors
  - Generation of process heat

Complex Environment for Accelerator Applications in Energy and Environment

- Accelerator applications in energy and the environment operate in a complex environment with many constraints and forces at work:
  - Regulatory landscape, public perception, market incumbency, risk averse operational environment, nuclear nonproliferation (for ADS)

- Barriers to deployment:
  - lack of availability of systems that meet required performance levels for full-scale industrial application, typically a factor of ten or more beyond that which is commercially available
  - the need for accelerator systems that are both highly efficient and reliable, yet economically competitive with incumbent technologies, and
  - lack of pilot-scale applications of these new technologies to demonstrate their efficacy and performance.

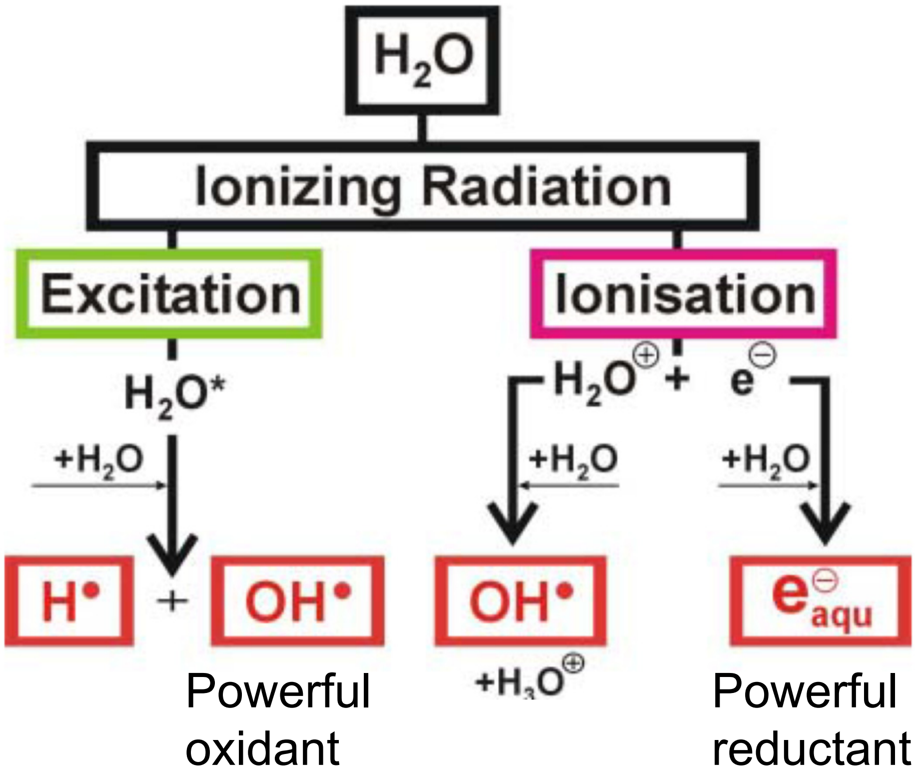
Electron Beam Radiation Processing

Potential Accelerator-Based Radiation Processing Applications

- Treating potable water and waste water
  - Domestic water supply, industrial effluent, water reuse
  - Disinfection, pathogen reduction, removal of disinfection byproducts, removal of pharmaceuticals
- Treating sewage sludge
  - Disinfection for subsequent fertilizer use
- Treating medical waste
  - Disinfection
- Removing pollutants from stack gases
  - Reduction in NO_x, SO_x, and Hg
  - Produces high-quality fertilizer as byproduct
- Environmental remediation of hydrocarbon contaminated soil
  - Cleanup of oil drilling sites
- Treating asphalt to improve wear resistance

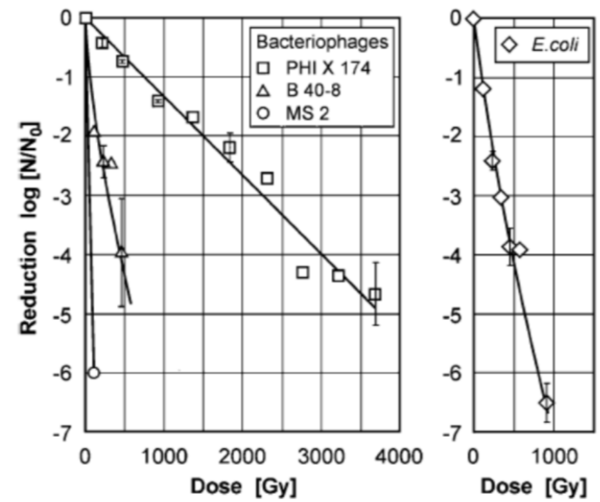
Radiation Chemistry

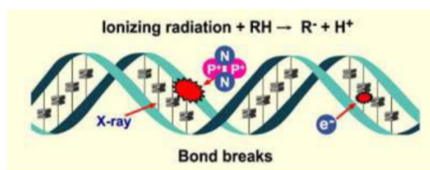
- Water Radiolysis: formation of free radical species in aqueous solutions by ionizing radiation
  - OH radical is powerful oxidant, with reaction rates with organic molecules 6-10 orders of magnitude greater than ozone, a powerful disinfectant
  - Aqueous electron is powerful reductant
- Oxidation/reduction reactions take place "instantaneously"



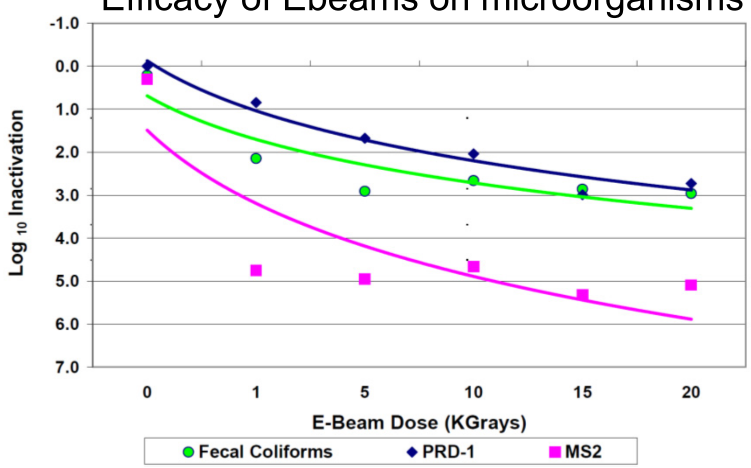
Electron-beam treatment of water, wastewater, sludge

- Decades of research has shown that electron-beam driven radiation chemistry is effective in
  - non-selective destruction of organics:
    - Pharmaceuticals and endocrine disruptors
    - Toxic Organic Chemicals, pesticides
    - Disinfection by-products
  - disinfection by elimination of microorganisms

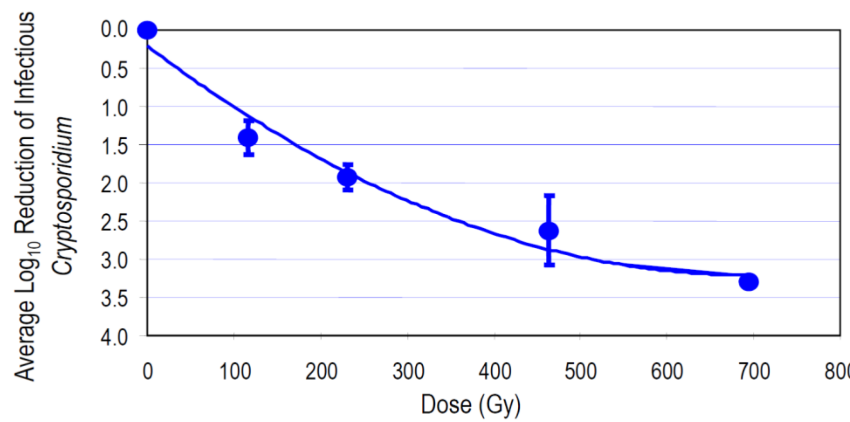




Efficacy of Ebeams on microorganisms

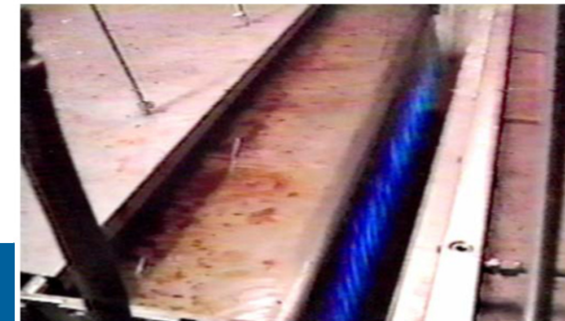


Electron Beam Inactivation of *Cryptosporidium* (*Potable Water*)



Requirements and Economics: Worked Example for Water Treatment

- Miami Pilot Plant demonstrated efficacy and measured dose delivery efficiency



	Pilot Plant	Plant at Scale	Notes
Million gals/day	0.14	10.0	Population of 100,000
Beam Power [kW]	75	6300	
Dose [kGray]	8.3	10.0	
Capital Costs [$M]	2.35	31.5	Assume $5/Watt
Amortized Capital Costs [$k/day]	0.58	7.77	Amortized over 20 years
Ops cost [$k/day]	0.98	14.9	75% electrical efficiency; includes labor costs
Cost [$/m^3]	2.87	0.60	

Virginia Key WWTP (Miami, FL) Large Scale Studies

Treated Water: 100 – 150 gallons per min.

- Chlorine cost is $0.09/m^3

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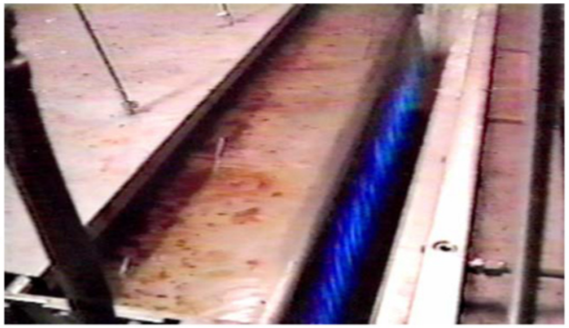

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Sludge

- Sewage sludge is nutrient-rich and properly disinfected is valuable fertilizer
- Commercial use of irradiation to disinfect sludge began in early ‘70s
  - EPA approved 10 kGy for treatment of sewage sludge, using either gamma or Ebeam to meet the definition of a process to further reduce pathogens (PFRP).
- Pilot scale studies using ionizing radiation in Canada, US, Brazil, India, Russia, South Korea, Japan, Austria.

10 *J. Engohang-Ndong et al. / Radiation Physics and Chemistry 112 (2015) 6–12*

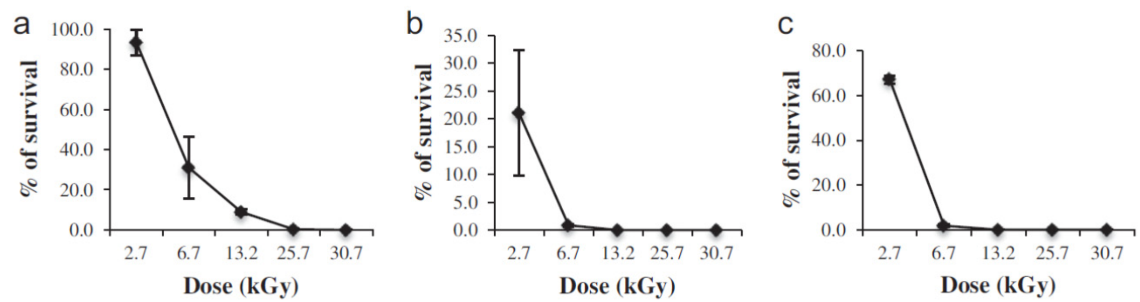


Fig. 4. Effect of electron beam irradiation on bacterial survival in municipal sewage sludge samples. (a) survival of total heterotrophic bacteria, (b) survival of total coliforms, and (c) survival of fecal coliforms.

- Large municipal water treatment facility with 100 million gallons/day would require ~500 kW beam power to treat sludge
- Unit costs are in the range of $60/dry ton, compared to ~$250/dry ton for alkaline stabilization, and significantly less than incineration
- Challenges: conservative industry, ease of operation and reliability, large CAPEX costs, large scale requires high power

Flue Gas Treatment

- High power E-beams remove NO_X and SO_X with high efficiency from coal-fired flue gas
- A number of facilities worldwide have installed Ebeam systems to treat flue gas. All plants use DC low-energy systems (<1 MeV).
- Hirshfield design: 250 kW at 2 MeV for 100 MWe:
  - 3 kGy dose gives 70% SO_x and 30% NO_x reduction;
  - Requires 9 kGy for higher removal implying 750 kW e-beam
  - 500 Mwe plant would require a fleet of 1 MW units to provide adequate redundancy
- Unit costs are competitive with traditional processes (A. Chmielewski)

	Capital Cost ($/kW)	Annual Operating Cost ($/MW)
Wet de-SO2+SNCR	205-270	15,250-31,050
Ebeam	160	7,350

- Challenges: high power, high reliability

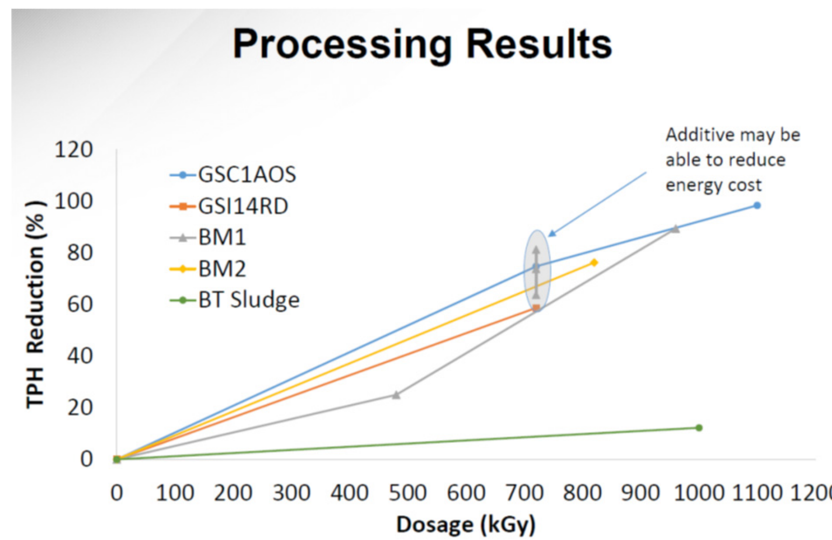

Pilot flue-gas treatment plant in Poland
Photo courtesy of A. Chmielewksi, Institute of Nuclear Chemistry and Technology

Four 260 kW units (700 keV); two heads on two parallel process vessels

Environmental Remediation

- Pollution of soils by organic hydrocarbons - major environmental issue: oil spills, drill site soil and water contamination
- E-beam irradiation: removes up to 99% hydrocarbon contaminants in soils with 100 kGy-1 MGy
- Requirement: 500 kGy delivered to 1000 cubic yds/day requires **7.5 MW Ebeam at 10 MeV**
- Unit cost is lower than the cost to excavate/haul the soil away
- Challenges: very high power, portability, fieldability

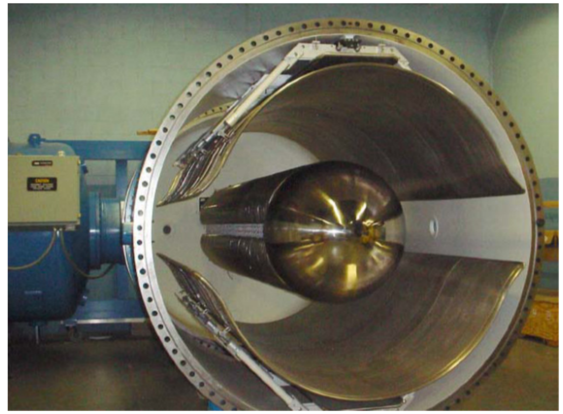
Decontamination cross section for a 10 MeV beam into a high-clay-content 5% contaminated soil



Courtesy D. Staack, TAMU

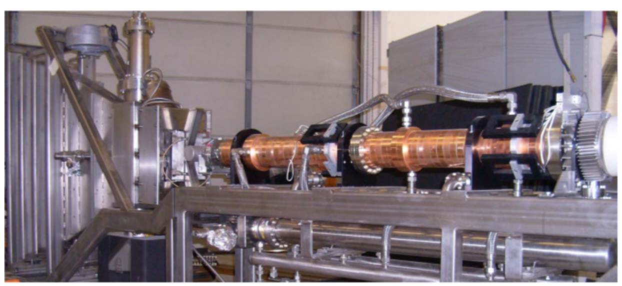
Selection of Commercial Ebeam Systems

Advanced Electron Beams: compact factory-sealed accelerator; 27 cm dia; 33 cm hgt.



IBA/RDI Dynamitron

ELV-12 BINP with EB Tech; 1 MeV, 400 kW



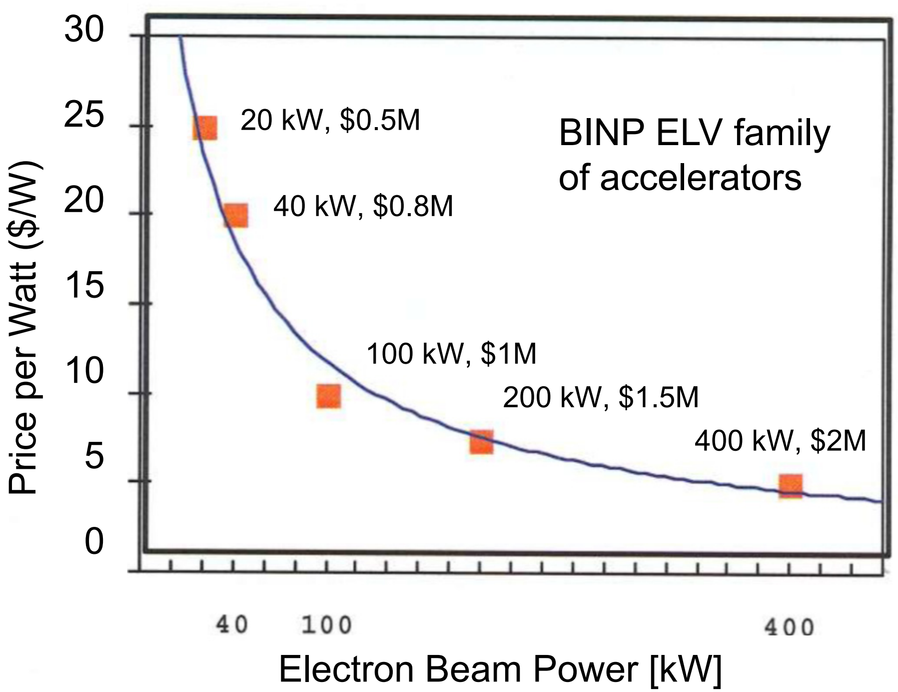
Mevex 10 MeV, 30 kW

BINP ILU accelerator

6 pass 7 MeV 700 kW Rhodotron (IBA)

Key Issues and Themes

- Extending beam power reach of E-beam systems
  - Emerging applications require very high beam power, x10 beyond today
- Costs, both capital and operating
  - Large entry costs
  - High power requires significant electrical power
- Improving power conversion efficiency (wall plug to E-beam)
  - Electrical efficiency ranges from 25% and 75%; higher efficiencies for DC low energy accelerators, lower efficiencies for microwave linear accelerators.



Key Issues and Themes

- On-demand use 24/7 requires very high reliability and availability and very robust engineering design
  - Requires same of better reliability compared to other industrial equipment
- Ease of Operation

vs.

- Lack of familiarity with E-beam technologies
- Industrial credibility
  - Credibility of industrial supplier is key
- Lack of pilot-scale and demonstration facilities to extend basic science and establish credibility

Accelerator Capability and Performance Targets

	Demo/small scale	Medium Scale Low Energy	Medium Scale High Energy	Large Scale High Energy
Description	Demo and pilot-scale low-energy systems	MW-class, industrial-scale, low-energy DC systems	MW-class, industrial-scale, high-energy systems	10 MW-class, industrial-scale systems based on RF technology
Applicability to E&E Needs	Sterilization, R&D	Flue gas, wastewater	Wastewater, sludge, medical waste	Wastewater, sludge, medical waste
Electron Beam Energy	0.5–1.5 MeV	1–2 MeV	10 MeV	10 MeV
Electron Beam Power	>0.5 MW	>1 MW	>1 MW	>10 MW

Near-Term High-Impact Accelerator R&D Priorities

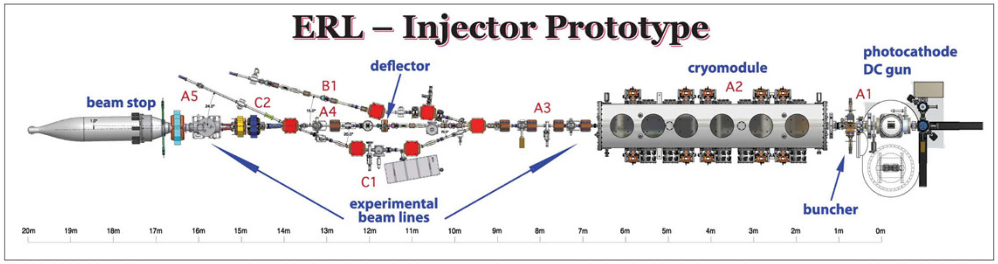
- DC accelerator systems:
  - Improve reliability aspects of high voltage and power conversion systems; improve reliability with respect to high-voltage breakdown, insulators, capacitors, and other HV system components.
- NCRF-based linacs:
  - Optimize RF cavity designs for low-energy, high-current electron linacs targeting 90% efficiency (RF to beam).
- SRF-based linacs:
  - Reduce cryogenic losses through high-quality factor SRF structures.
  - Optimize SRF structures for high-current, low-energy applications (a very different optimization from that of DOE High Energy Physics programs
- Beam dynamics:
  - Deploy modern beam dynamics codes in new contexts relevant for low-energy, very high-current applications. Simulate beam loss and stray halo particle loss; design and shielding of accelerating columns for Ampere-class beams.
- Electron sources:
  - Develop and demonstrate (including characterization of beam halo) ampere (and multi-ampere?) class sources with appropriate beam quality for injection into an accelerator (either DC or RF linac, most severe for SRF). High-current (5 A) sources exist but at 10s of kilovolts. There is a gap in taking this high current to high enough energy to couple into an accelerator system.

Long-Term High-Impact Accelerator R&D Priorities

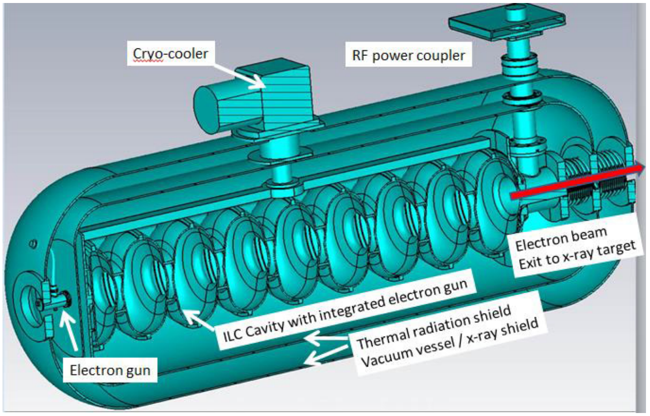
- DC accelerator systems:
  - Develop approaches for handling very high DC beam currents in accelerating columns.
- SRF-based linacs:
  - R&D for hi-Tc SRF materials
  - Direct-conduction cooling utilizing cryocoolers.
  - Cost savings through alternative fabrication methods
  - Develop cold-cathode SRF gun technology
- RF power systems:
  - Total system: System efficiency greater than 80% is desirable with capital cost less than $3/W.
  - Klystron, Magnetron, Solid-state sources: Demonstrate high RF system efficiency at relevant average powers.
- Electron sources:
  - Demonstrate high-current source coupled to an accelerator system with appropriate halo control and transport in the accelerator system
- Portable high power systems:
  - Demonstrate system-level engineering for portability, fieldability and turn-key operation.
- System level:
  - Multi-megawatt high-energy systems with target electrical efficiency and availability/reliability.
  - Demonstrate NCRF-based system capable of >50% AC-beam efficiency, including RF and all support systems in the 10 MeV, > 1 MW-class
  - Demonstration of SRF-based system capable of >50% AC-beam efficiency, including RF and cryogenic cooling in the 10 MeV, > 1 MW-class
- Commercialization:
  - Demonstrate capital cost goals (<$5–10/W depending on system).
  - Demonstrate wall-plug to beam-power efficiency goals (>50–75%).

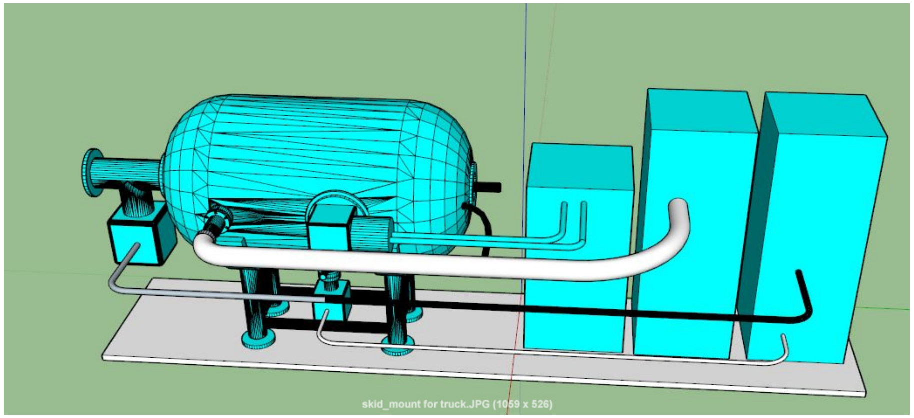
Emerging Technologies (see Boulware, FRB2IO02)

- Superconducting technology has the potential to reach high beam powers at high energy
  - Capable of continuous-wave operation
  - Efficient rf power to beam power transfer
  - However, cryogens introduces complication and challenges overall wall-plug power efficiency
- Example: Cornell Energy Recovery Linac Injector: 4 MeV x 75 mA = 300 kW
- New developments with potential to expand reach of low energy high average power Ebeams
- Higher temperature superconductors:
  - Nb_3Sn coated cavities at 4 K
  - Simplified cryostats and Commercial Cryocoolers



Courtesy Cornell University





Courtesy FNAL

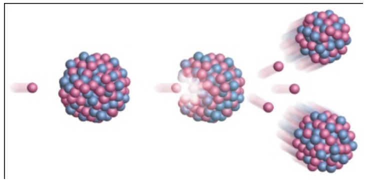
Proton Accelerators for Advanced Nuclear Systems

Applications of Accelerator Driven Systems

- Accelerator Driven Systems may be employed to address several missions, including:

Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.

Generating electricity and/or process heat.



Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

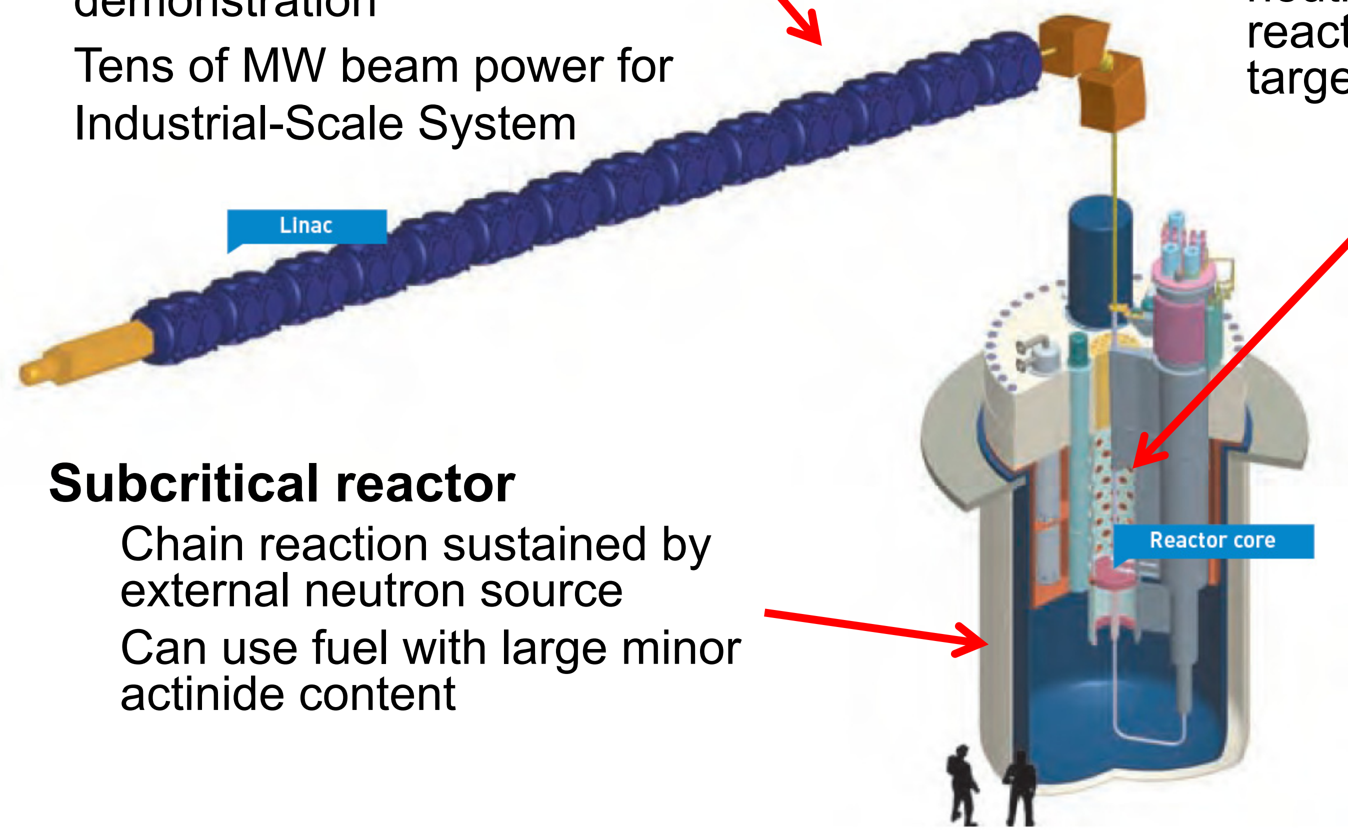
Accelerator Driven Systems

High-power, highly reliable proton accelerator

- ~1 GeV beam energy
- ~1 MW of beam power for demonstration
- Tens of MW beam power for Industrial-Scale System

Spallation neutron target system

- Provides external source of neutrons through spallation reaction on heavy metal target

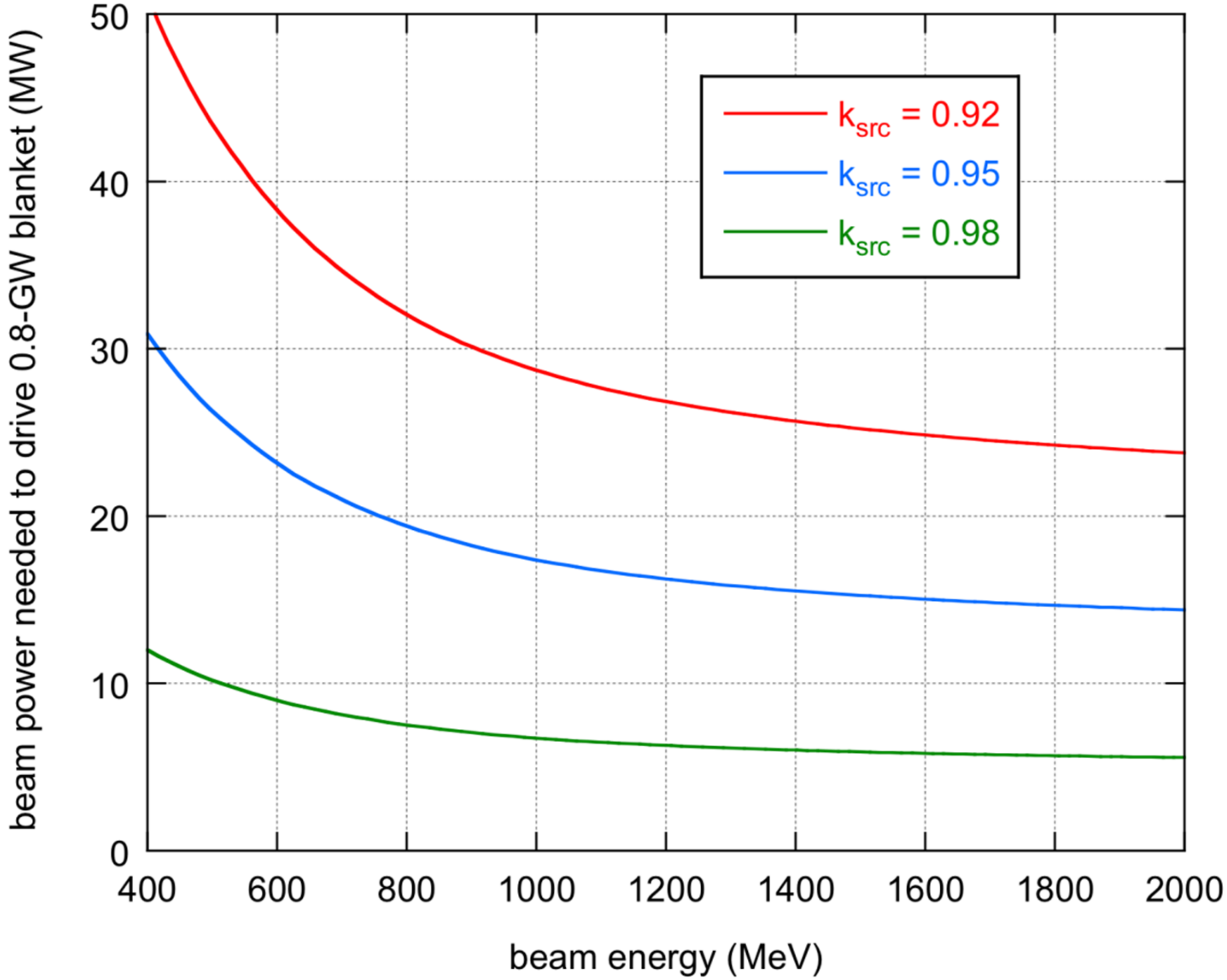


Subcritical reactor

- Chain reaction sustained by external neutron source
- Can use fuel with large minor actinide content

Beam power depends on effective neutron multiplication factor

$$P_{th} = G_0 \frac{k_{src}}{1-k_{src}} P_{beam}$$



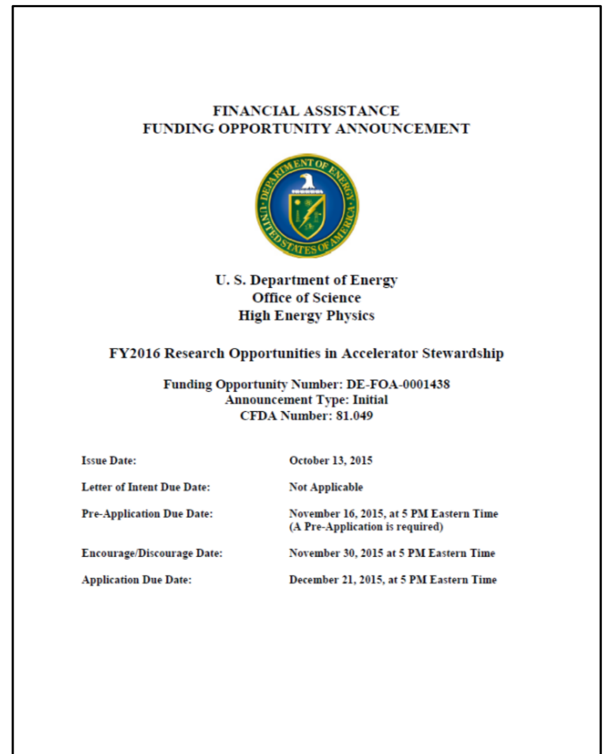
Typical values are N_0/N_b ~25-30 for E_p = 1 GeV, $G_0 \approx$ 2.3-3.3

ADS Accelerator Requirements and Challenges

- Proton beam energy in the ~GeV range
  - Efficient production of spallation neutrons
  - Energy well-matched to subcritical core design
  - Minimize capital cost
- Continuous-wave beam in the > 10 MW regime
  - High power required for industrial systems to justify capital expense
- Low beamloss fractions to allow hands-on maintenance of accelerator components (< 1 W/m)
  - 1 W/m proton loss activates SS to ~100 mRem/hr
- Accommodate high deposited power density (~1 MW/liter) in the target.
- Beam Trip Frequency: thermal stress and fatigue in reactor structural elements and fuel assembly sets stringent requirements on accelerator reliability
- Availability typical of modern nuclear power plants

Summary

- Accelerators have tremendous potential in Energy and Environmental applications
- Deployment requires significant challenges to be met
- There is exciting and challenging R&D needed to meet the demanding requirements of E&E applications



FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Science
High Energy Physics

FY2016 Research Opportunities in Accelerator Stewardship

Funding Opportunity Number: DE-FOA-0001438
Announcement Type: Initial
CFDA Number: 81.049

Issue Date:	October 13, 2015
Letter of Intent Due Date:	Not Applicable
Pre-Application Due Date:	November 16, 2015, at 5 PM Eastern Time (A Pre-Application is required)
Encourage/Discourage Date:	November 30, 2015 at 5 PM Eastern Time
Application Due Date:	December 21, 2015, at 5 PM Eastern Time