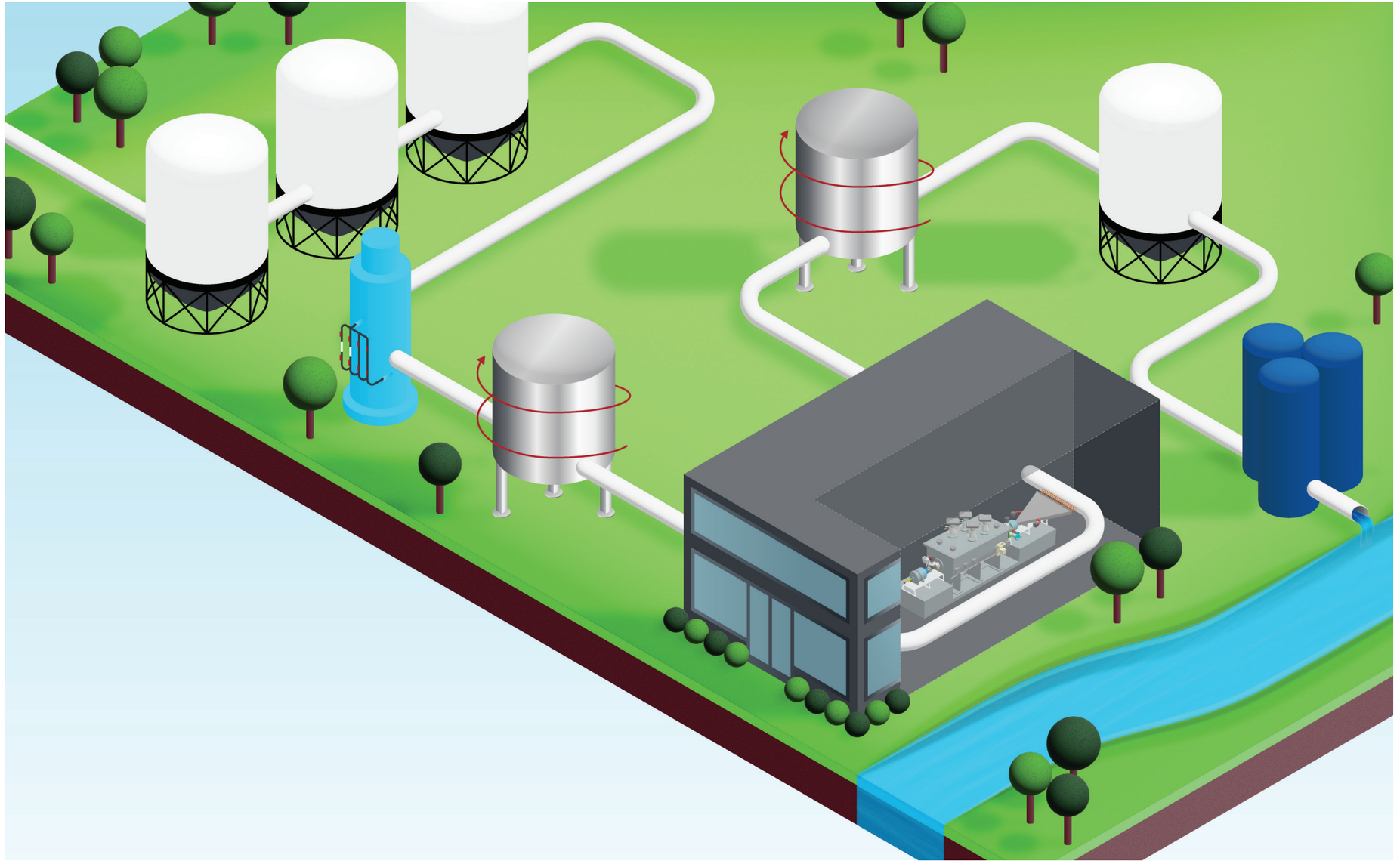
Environmental Remediation

Science and Technology for Society:

PFAS Destruction, Municipal and Ballast Water Treatment, and Soil Remediation

Fermilab



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Fermilab's Illinois Accelerator Research Center

The mission of IARC

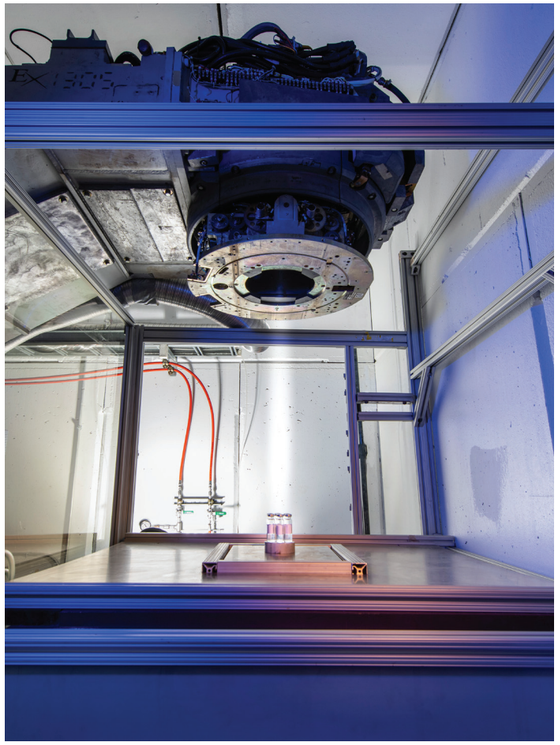
The Illinois Accelerator Research Center, or IARC, which is located at Fermilab, was built and established in conjunction with the State of Illinois. Its mission is to facilitate and actively promote technology transfer and partnerships.

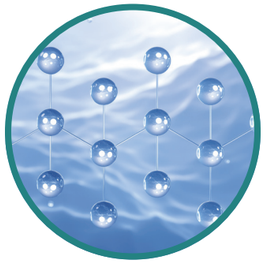
IARC engineers and scientists work side by side with industrial partners, universities and federal agencies to research and develop accelerator science and technology breakthroughs and translate them into applications that benefit the nation's health, wealth and security.

Accelerator research and environmental remediation

Experts in science and industry are seeking ways to eliminate contamination from the environment.

Engineers at Fermilab's IARC are experts in high-energy electron beam accelerators. Electron beams are excellent at destroying, for example, PFAS in the environment.





Destruction of PFAS
Addressing one of the biggest contamination concerns in the world

Municipal water treatment
Providing on-demand sterilization of water

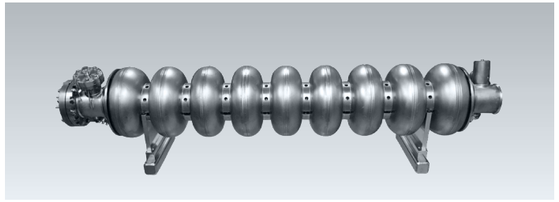
Ballast water treatment
Mitigating the problem of invasive species

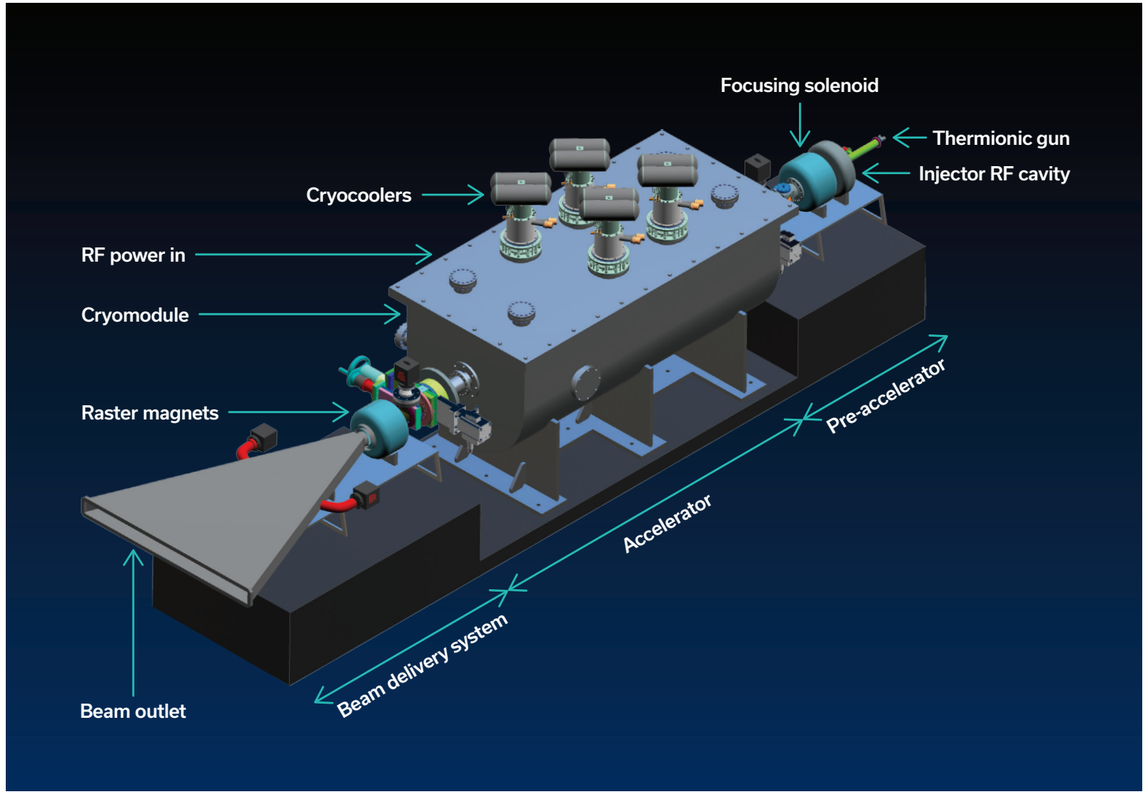
Destruction of toxins in soil
Helping the federal government manage legacy waste

Our solution

Industrial SRF accelerators

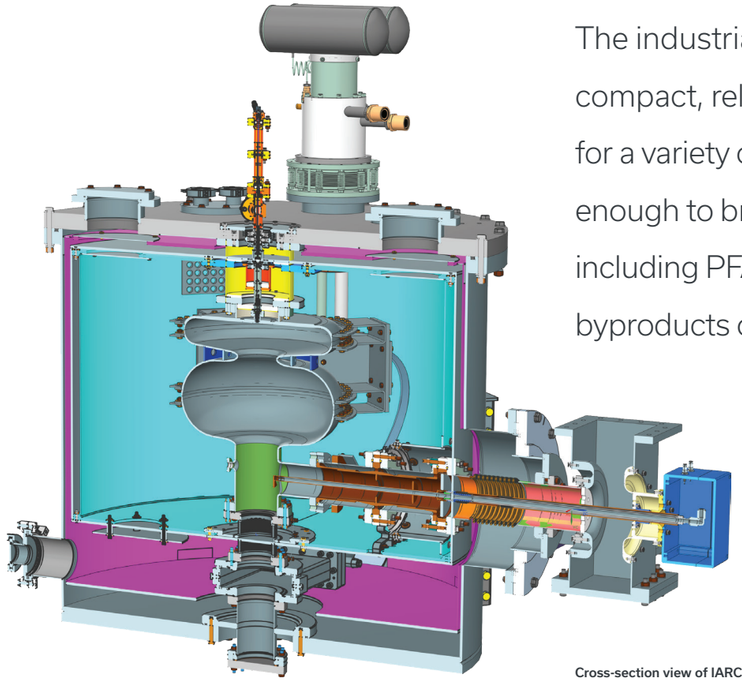
By leveraging Fermilab's world-leading expertise in particle accelerators and decades of research and development experience, IARC scientists and engineers developed a superconducting radiofrequency (SRF) accelerator that can be used for environmental remediation and other industrial needs.





Key accelerator features

Type	Superconducting electron beam accelerator	**Cooling method**	Conduction cooled via crycoolers
Energy	10 MeV	**Length**	15 ft+
Power	20 kW+	**Width**	6 ft
Frequency	650 MHz / 1.3 GHz	**Height**	6 ft
Operation mode	Continuous wave	**Weight**	3,000 lbs



Cross-section view of IARC's vertical industrial SRF accelerator

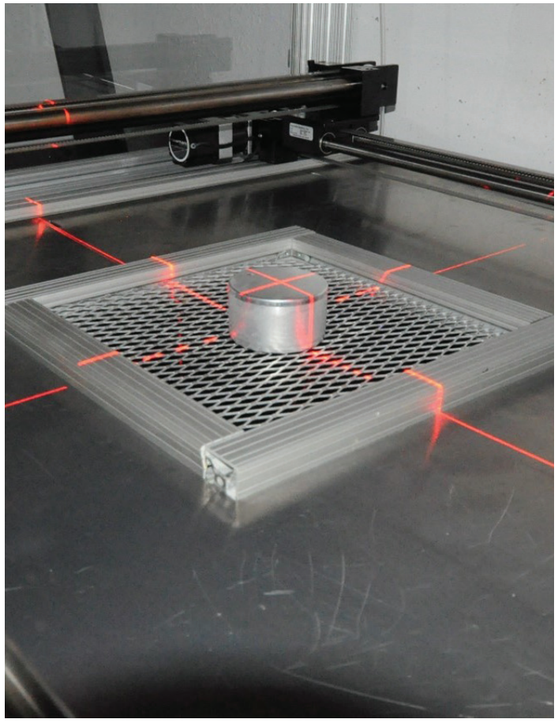
The industrial SRF accelerator is compact, reliable and designed to work for a variety of applications. It is powerful enough to break down chemicals, including PFAS, without creating any byproducts or hazardous materials.

Experimental testing

Sample testing capabilities

The Accelerator Applications Development and Demonstration tool, or A2D2, is a repurposed medical 9-MeV electron accelerator scientists and engineers use to verify electron beam proofs-of-concept for individual applications.

With adjustable dose rates and sample positions available, A2D2 is used by industry, universities and other government labs.



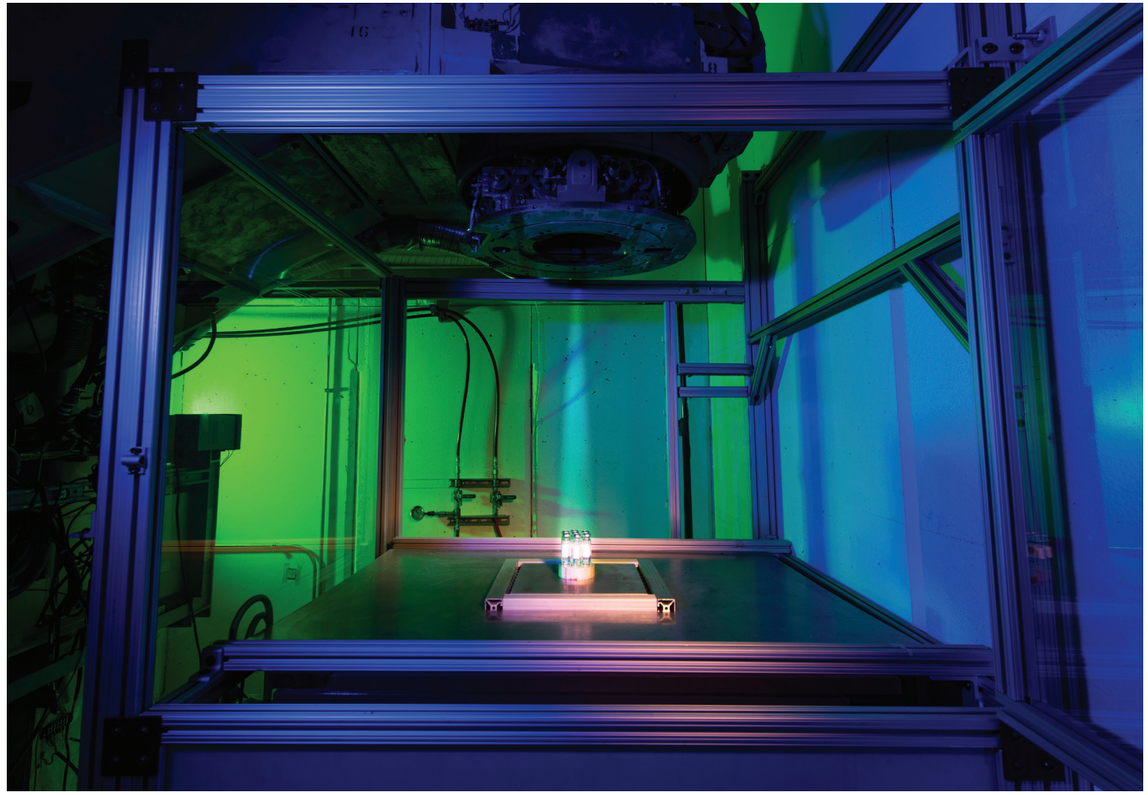
A2D2 test stand specifications

Beam energy	9 MeV
Nominal beam power	1.2 kW
Beam orientation	Vertical
Dose rate	0.2 to 1.2 kGy/sec

A2D2 can accommodate a wide variety of sample containers and flat stock. A typical sample size container is 3.5 inches in diameter and 2 inches high.

Accelerator Application Development and Demonstration — A2D2

The electron beam — or e-beam — treatment process has proven effective at breaking down a wide range of contaminants. It facilitates non-thermal destruction of organic contaminants using free radicals produced by e-beam interactions (e.g., e-beams induce dechlorination and cleavage of aromatic carbon rings, even in traditionally difficult to treat organic contaminants such as PCB, PAH, dioxanes and chlorinated solvents). Research has proven that e-beam is also a viable treatment option for per- and polyfluoroalkyl substances, also known as PFAS.

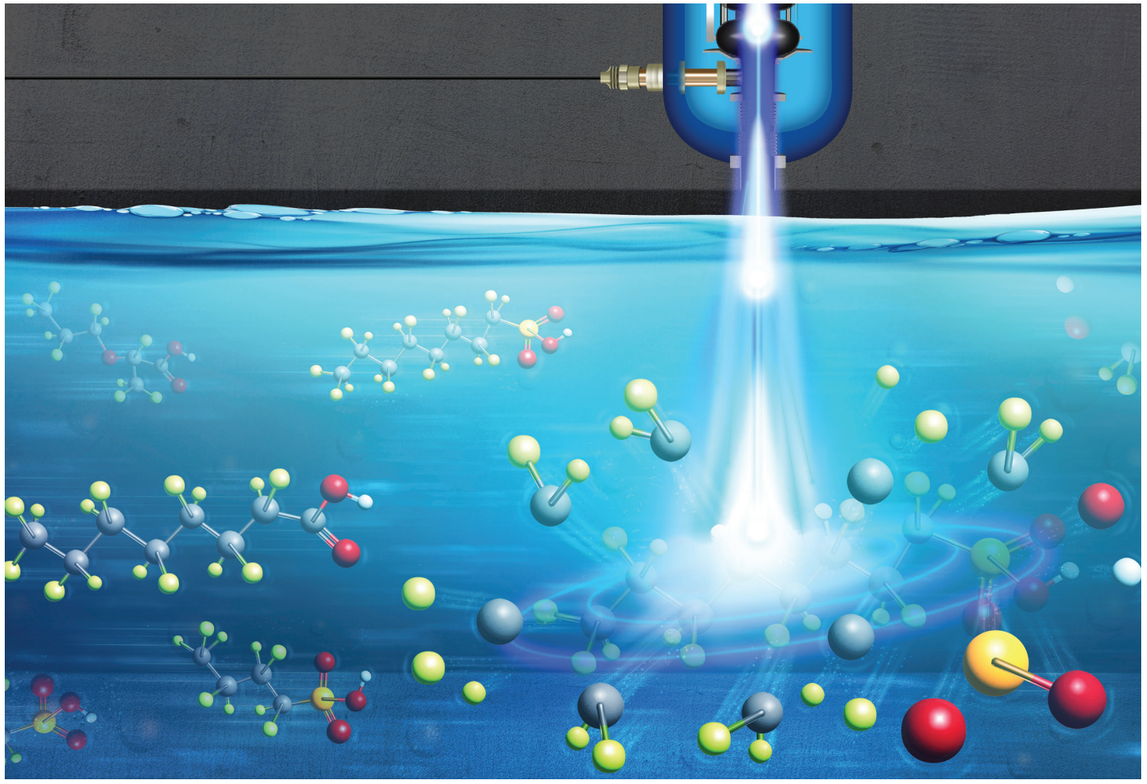


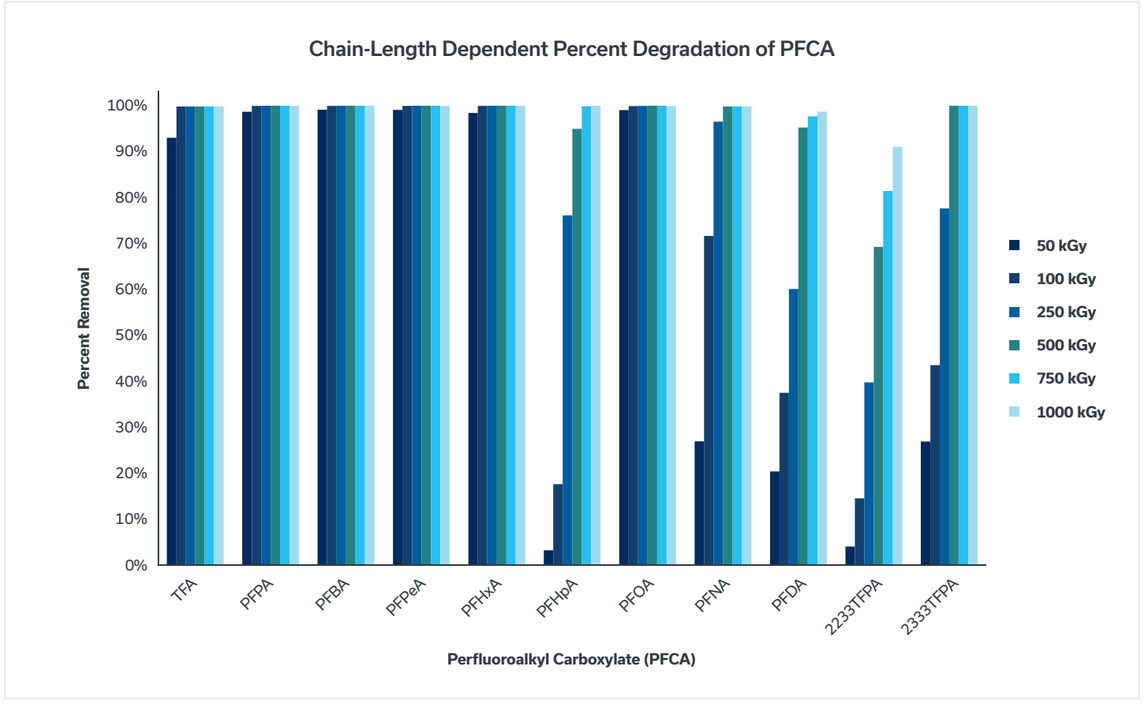
Using electron beam to destroy PFAS

Testing and results

IARC is engaged in environmental remediation of PFAS in water and soil. In a process called water radiolysis, the electron beam creates active species that break down PFAS.

Fermilab has demonstrated that electron beams can be used to create aqueous electrons which effectively destroy a wide range of PFAS in water including PFOA, PFOS, PFBS, PFHxS, PFNA and HFPO-DA.





The results above from analysis of e-beam treated PFCA validated that low-molecular-weight, short-chain perfluoroalkyl carboxylic acids (PFCA), a type of PFAS, were efficiently removed. These results indicate that short-chain PFCA are more susceptible to e-beam treatment than short-chain perfluoroalkane sulfonic acids and sulfonates (PFSA), for example. It also shows that perfluorooctane sulfonic acids (PFOS) and perfluorooctanoic acids (PFOA) appear to be the most susceptible to e-beam treatment. However, further testing is needed.

This work is described in a joint Fermilab/3M study, "Degradation of Poly- and Perfluoroalkyl Substances (PFAS) in Water via High Power, Energy-Efficient Electron Beam Accelerator."

www.osti.gov/biblio/2349585

Using electron beam to treat municipal water

Testing and results

Using electron beams to treat biosolids, IARC worked with a large metropolitan water district to demonstrate complete destruction of fecal coliform (FC), increased recovery of phosphorous using an Ostara process, and increased energy recovery from carbon in biosolids. The study showed:

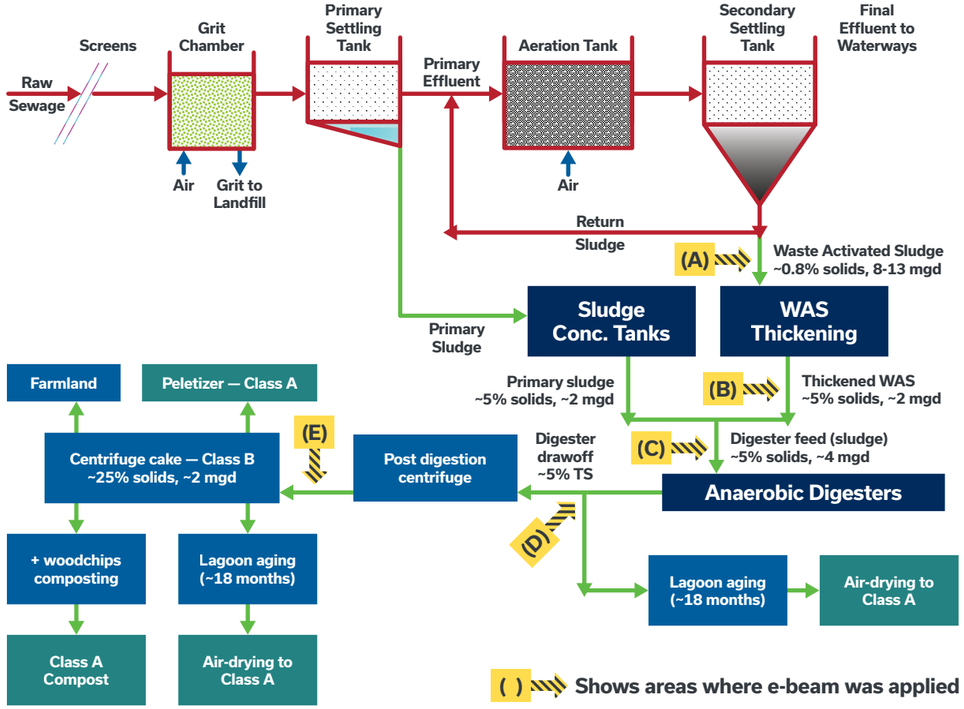
- 99.99% reduction of FC bacteria in the digester draw samples with the application of 10 kGy dose of e-beam
- 5 kGy dose to digester draw samples reduced FC concentration from 99.9% to 99.99% in duplicate analyses
- 2.5 kGy dose achieved 99.9% to 99.99% reduction of FC bacteria in duplicate analyses

E-beam treatment of water and other matrices is a proven technology. During treatment, a bulk of the e-beam beam energy is used to break down the water molecule into various charged species that are very effective at removing contaminants through both oxidative and reductive routes.

E-beam treatment of water has already demonstrated the capability to:

- Increase dewaterability of sludges
- Remove toxic chemicals, such as pharmaceuticals, fuel additives, polychlorobiphenyls and solvents, and remove toxic chemicals from various matrices including agricultural runoff
- Reduce pathogens

Schematic of MWRD Stickney WRP Treatment Process



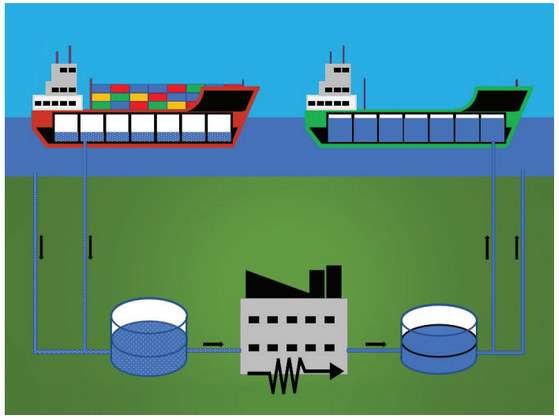
Process flow for treatment of raw sewage entering the facility and the output of Class A or Class B waste at Metropolitan Water Reclamation District's Stickney Water Reclamation Plant.

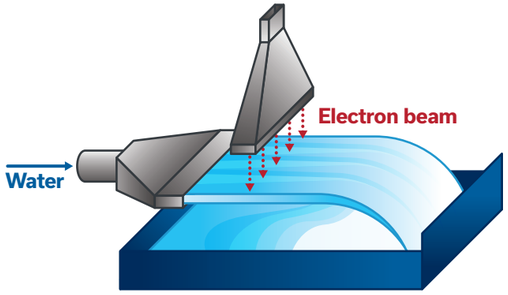
The cost of e-beam treatment is impacted by mass flow rate and dose delivered. The highest flow rate stream studied was at application area A (waste activated sludge), which has a flow rate of 8-13 mgd. Moving down the process flow the total flow rate decreases. Therefore, the cost to treat with a constant dose decreases. An exception is at application area C (digester feed), which doubles from application area B (thickened waste activated sludge) due to addition of a primary sludge flow.

Using electron beam to treat ballast water

Testing and results

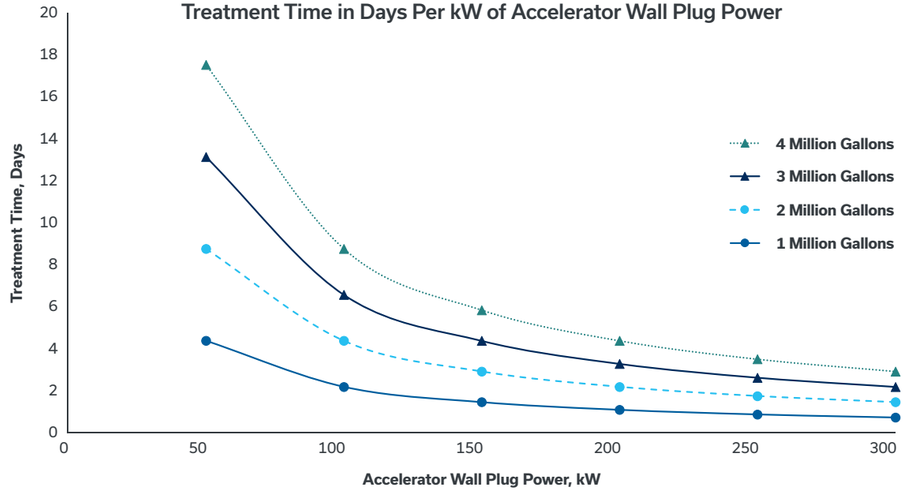
Ballast water is a major source of biological invasion between bodies of water. They damage and destroy the cells of harmful marine organisms, including viruses, bacteria and algae.

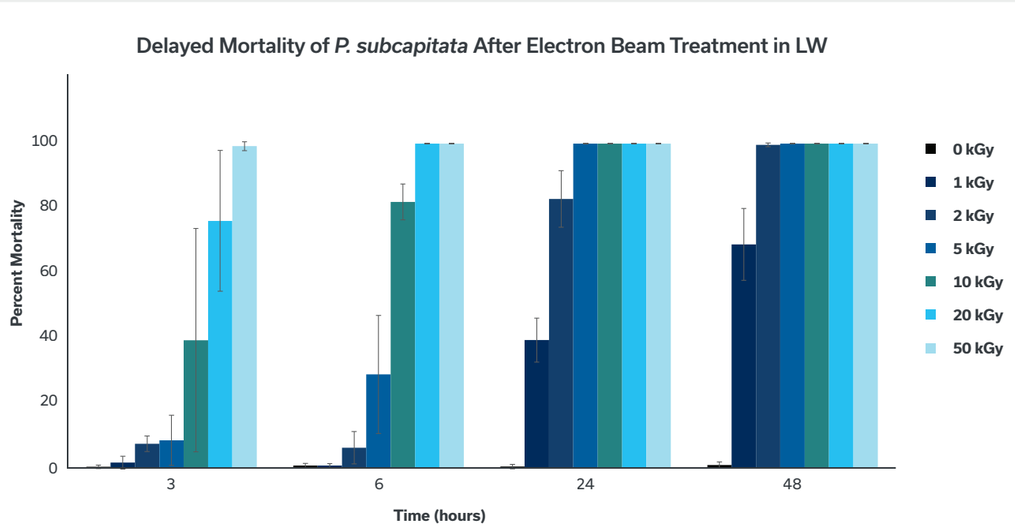




Fermilab teamed up with University of Wisconsin-Superior to study the effectiveness of e-beam to treat organisms representative of the Great Lakes in ballast water discharge. Fermilab irradiated samples containing various organisms to total doses ranging from 1 to 50 kGy.

As shown at right, this research demonstrated that e-beam is an effective treatment for this use case, even at the low total dose of 2 kGy. High rates of mortality were observed 24 to 48 hours post-treatment for all species.





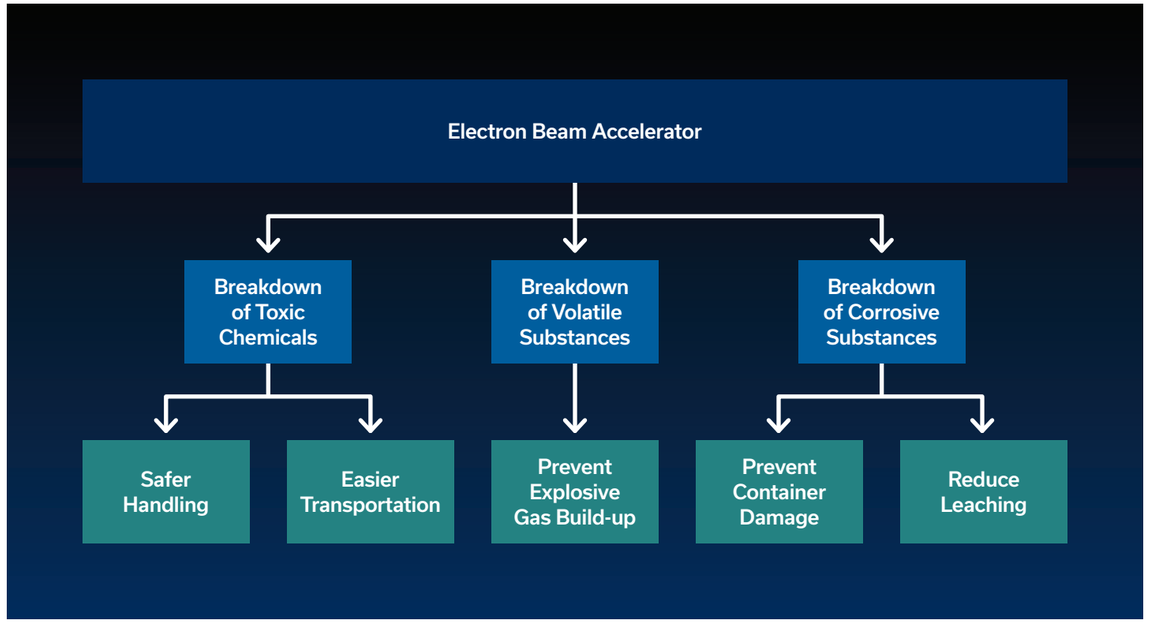
Using electron beam to destroy toxins in soil

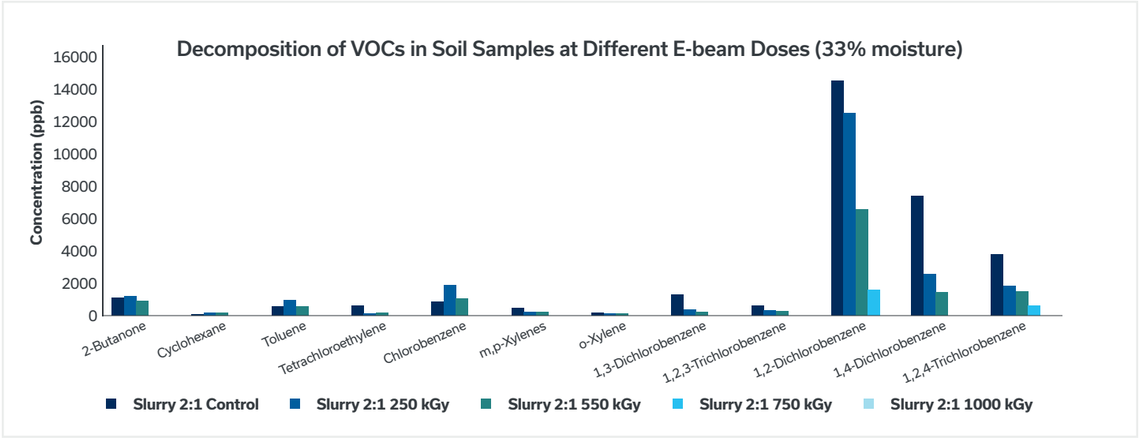
Testing and results

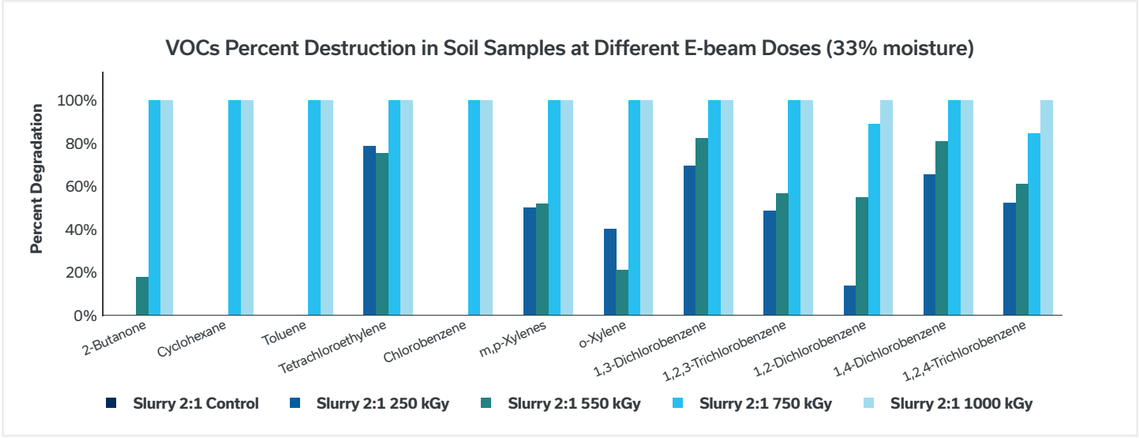
IARC seeks to evaluate the effectiveness of e-beam to destroy organic components in soil. This can reduce disposal costs by eliminating organic components and simplify disposal and transportation after treatment.

Potential benefits of using e-beam for soil treatment include:

- Reduced lifetime costs and improved overall safety
- Reduced transportation costs and secondary contamination due to the ability to treat wastes locally
- Reduced complexity of overall treatment process due to e-beam's ability to break down a wide range of contaminants



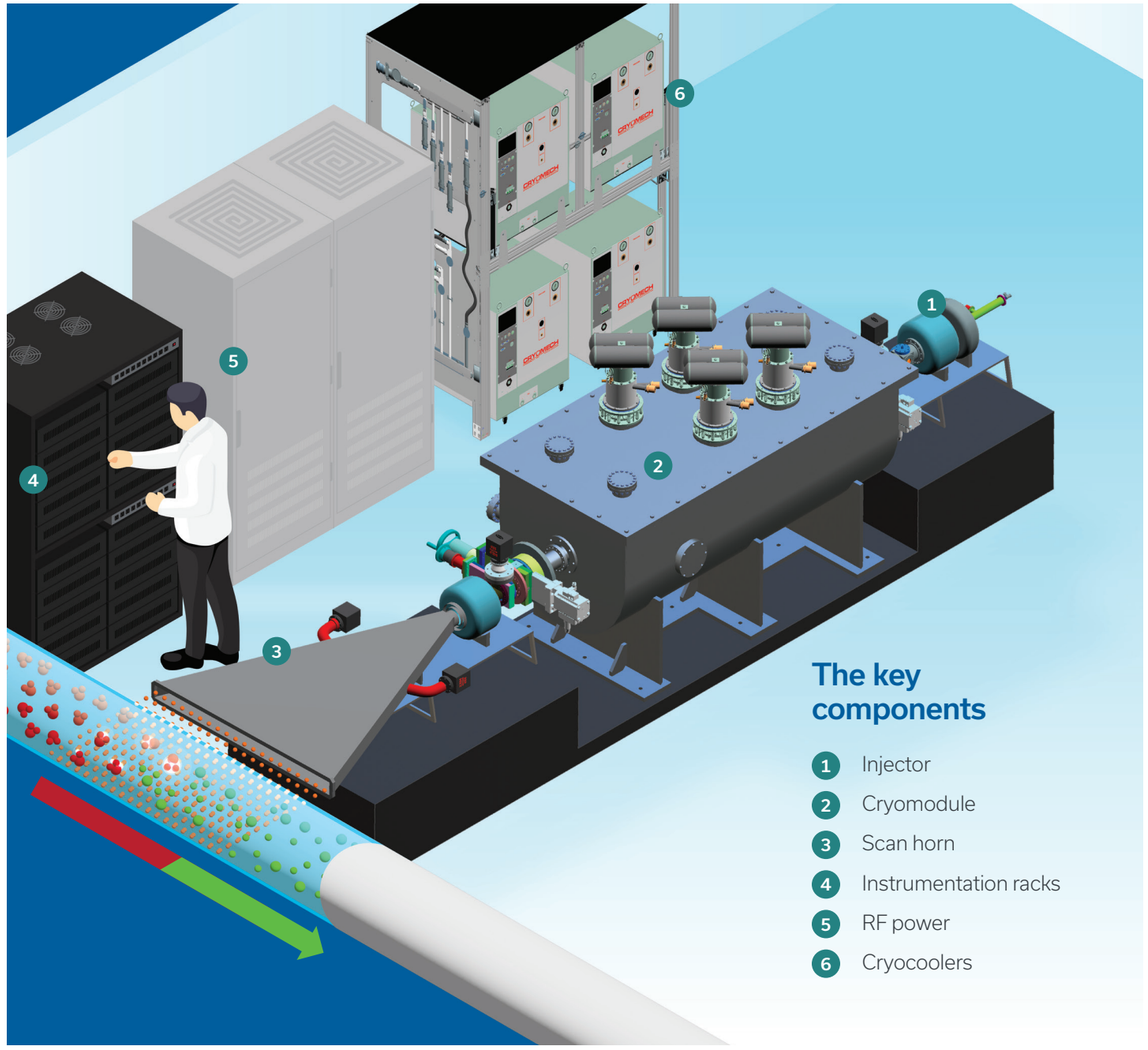




Preliminary sample work has demonstrated proof of principle and established a clear path forward for further sample work. The figures above show an example of post irradiation results of volatile organic compound (VOC) levels at various total doses.

As expected, degradation increased as the total dose increased. These results potentially show whether contaminants can be cost effectively decomposed via e-beam alone or whether additives would be required to increase the reaction rate or aid the e-beam irradiation, thereby reducing the overall power consumption.

Fermilab's flexible industrial SRF accelerator solution



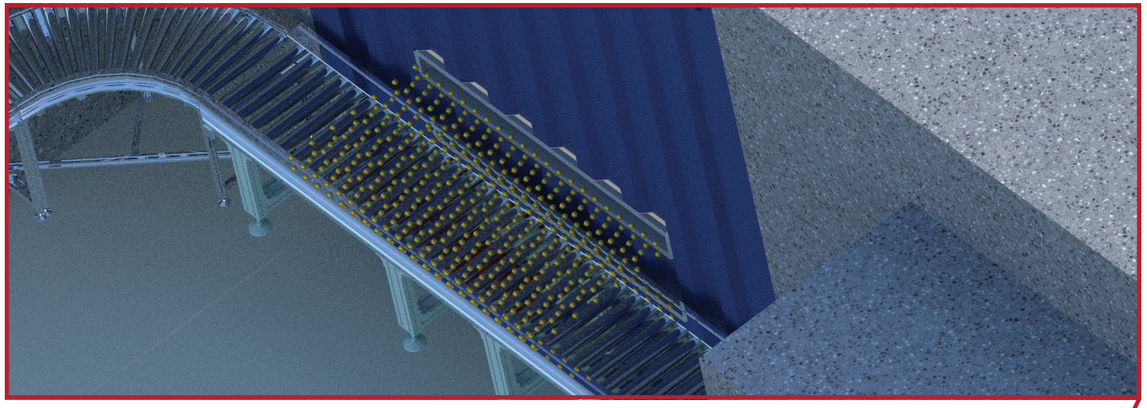
The key components

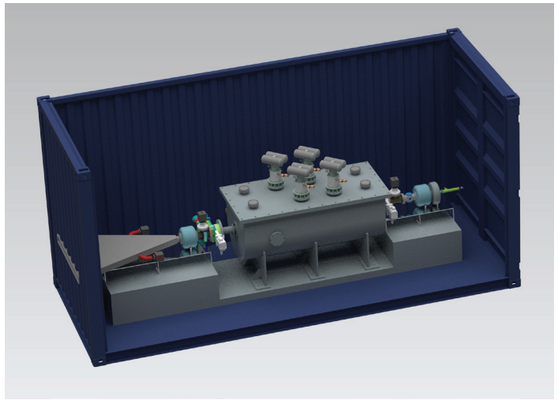
1. Injector
2. Cryomodule
3. Scan horn
4. Instrumentation racks
5. RF power
6. Cryocoolers

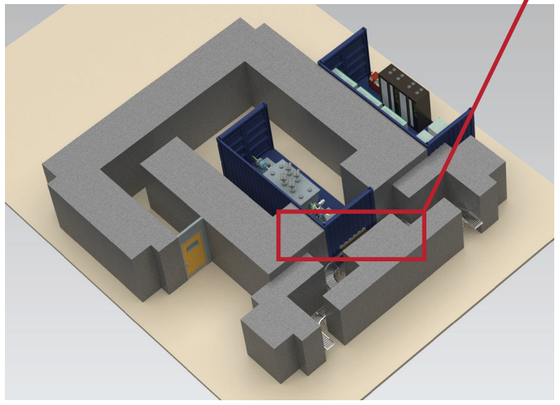
A drop-in solution

To address the problem where it exists, IARC has developed a transportable accelerator solution that enables the accelerators to be deployed at any location.

The accelerator can be powered by generators, cooled with mobile chiller systems and transported in standard containers to allow for deployment in a variety of spaces.



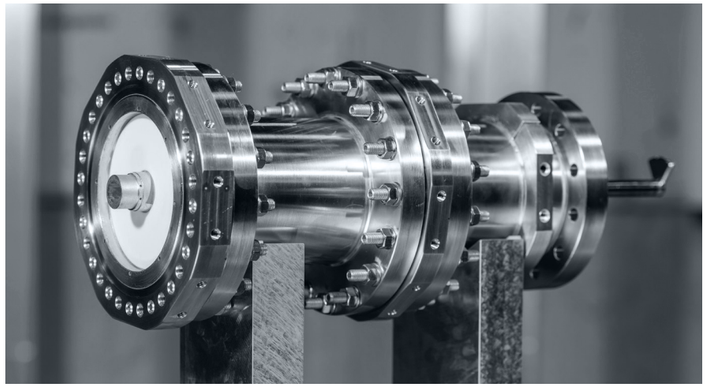




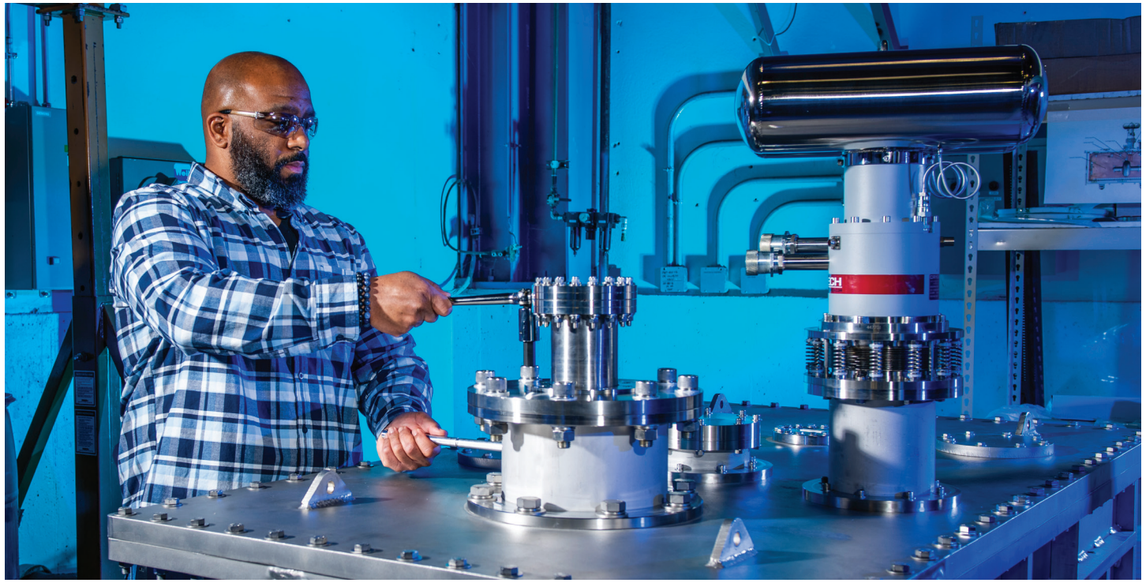
Cutting-edge accelerator technology

Globally recognized leadership

At IARC, industrial accelerator assembly and testing is underway with commissioning of the system to come. For more than 50 years, Fermilab engineers have been developing and testing the cutting-edge technology used to deliver world-class accelerators and science. For the past two decades, they have honed their expertise in superconducting radiofrequency technology.



Radiofrequency power coupler



An engineer assembles a conduction cooled super radiofrequency cryomodule

An IARC engineer assembles a radiofrequency power coupler for an industrial SRF accelerator

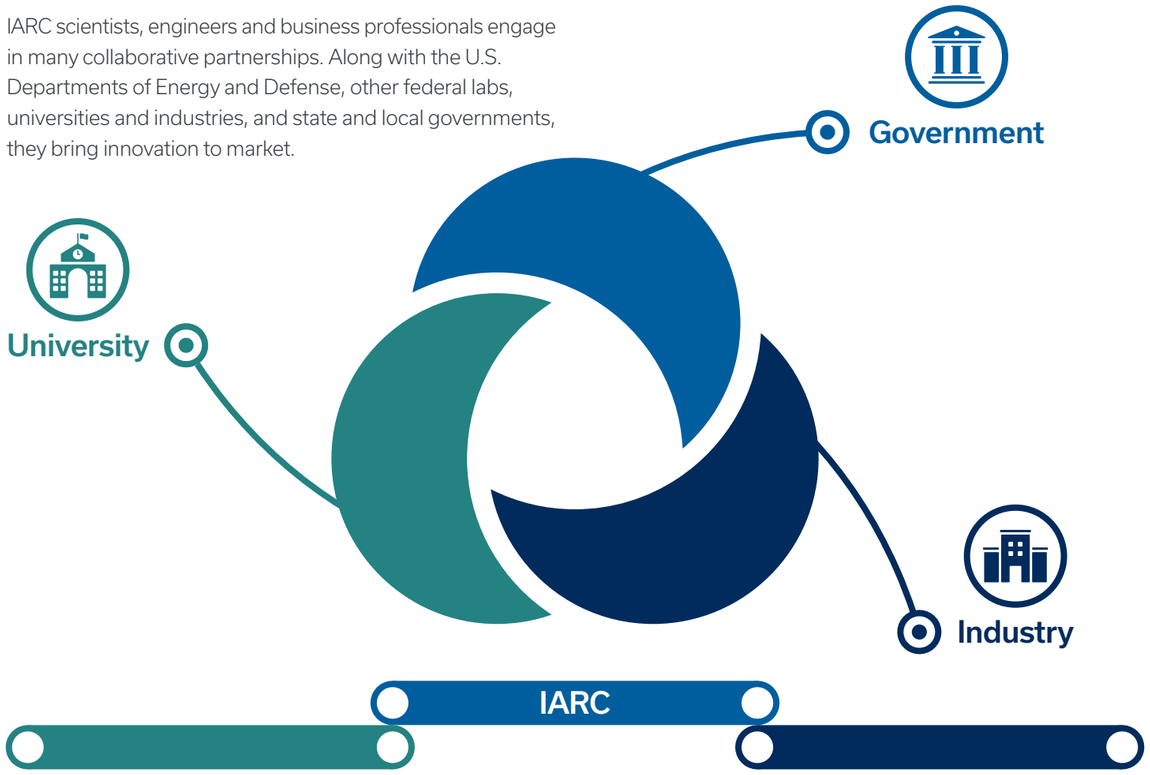
Fermilab engineers are continually pushing boundaries to keep America at the forefront of accelerator-based science and technology.

Cavity interior

Collaborative partnerships

Fermilab is built on collaboration.

IARC scientists, engineers and business professionals engage in many collaborative partnerships. Along with the U.S. Departments of Energy and Defense, other federal labs, universities and industries, and state and local governments, they bring innovation to market.



IARC is focused on bridging the gap between research and development and community and commercial readiness.

Fostering partnerships for innovation

Fermilab and IARC have several electron beam lines and test beds suitable for collaborative research including:

- 10 MeV pulsed electron beam accelerator
- Commissioned 10 MeV CW 2, maximum 12 mA electron beam accelerator
- Sample preparation area that can help our collaborators prepare for electron beam treatment
- CW 1.8 MeV 12 mA electron beam accelerator
- Secured controls and data acquisition system and office space
- Large suite of conference and training rooms

The Fermilab Office of Partnerships and Technology Transfer has a knowledgeable team to support SBIRs, CRADAs and Work for Others agreements.

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The Illinois Accelerator Research Center, also known as IARC, was established with support from the State of Illinois to industrialize Fermilab's technologies and, with its partners, to advance the next generation of technologies, products and applications to assist U.S. industry and support our science mission.

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